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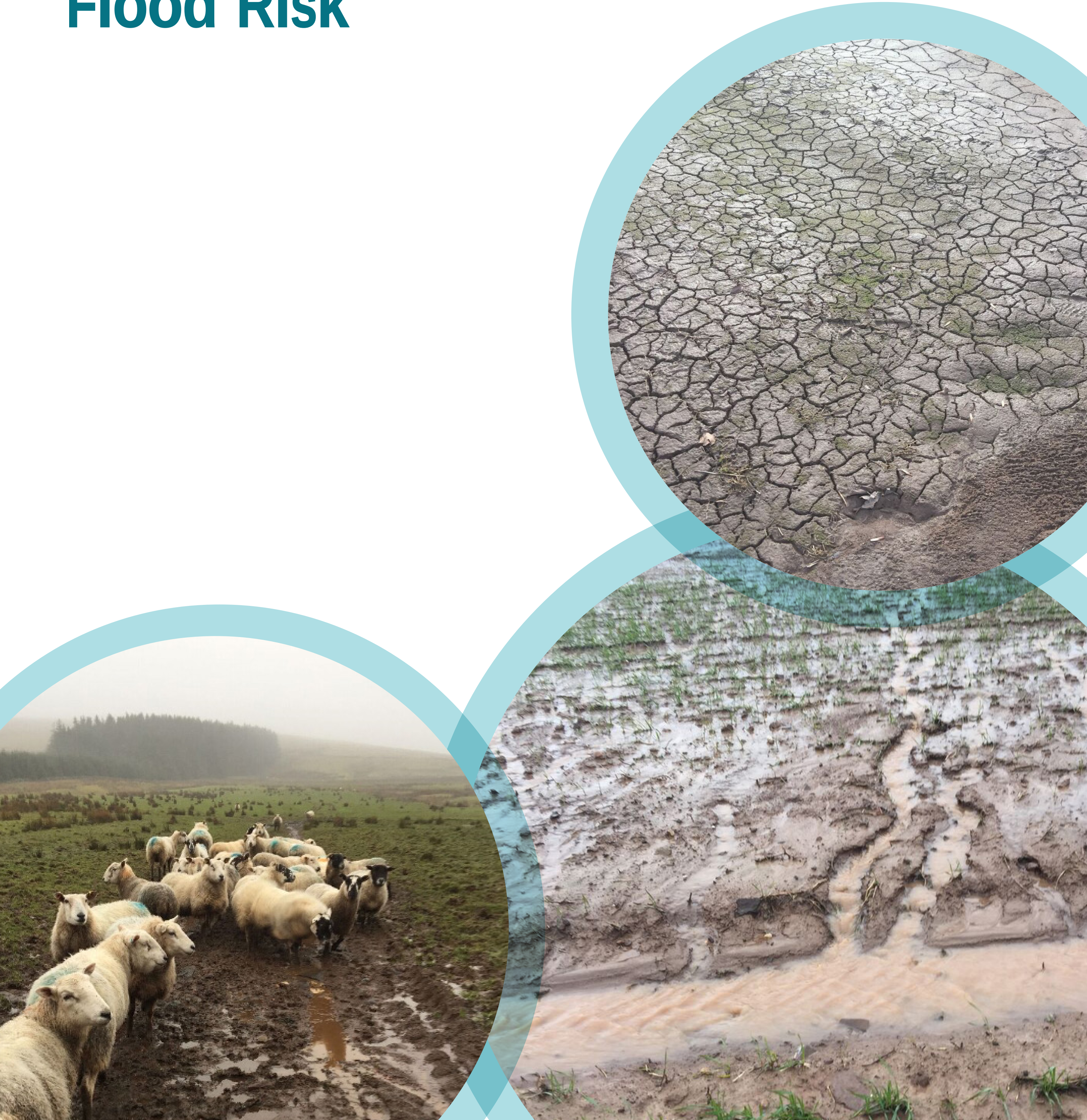
Effect of Soil Structure and Field Drainage on Water Quality and Flood Risk



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Executive Summary

Background: Are degraded agricultural drains and soils affecting flood risk and water quality in the winter in Scotland? Based on a questionnaire to Scotland's farmers, field monitoring from SEPA Catchment Coordinators and evidence from other regions, there is visual evidence of standing water on agricultural fields, degraded soil structure and poor investment in drain maintenance. Studies dating back to the 2000 floods in England and Wales reported that autumn land management when soils are wet cause's damage, and that drains are less effective due to decreased investment.

Research Undertaken

This report uses data from sampling of 120 fields from 4 catchments in Scotland to describe the state of soil structure in the winter. It uses the increasingly popular and easily interpretable Visual Evaluations of Soil Structure (VESS) and Subsoil Structure (SubVESS). The study was conducted in winter 2015/2016, which was the wettest on record, with Eastern Scotland receiving 228% its average rainfall in January. A total of 42 fields were sampled before and after intense and prolonged precipitation to observe soil structure changes resulting from winter rainfall.

Main Findings

We found severe soil structural degradation in 18% of topsoils and 9% of subsoils for 120 fields in 4 catchments across Scotland. The severe 2015/2016 winter precipitation caused a 30% increase in occurrence of severely degraded topsoils, as determined from sampling some of the same fields before and after this unprecedented weather event. Run-off, erosion and nutrient losses were about 10X from degraded parts of fields such as tramlines than either within the field or at less trafficked boundaries. There was some agreement between areas identified as structurally degraded and those ranked as being susceptible to topsoil compaction using a simple model. Farmers suggested widespread degradation of artificial drainage, with a visual assessment confirming poorly functioning systems.

Recommendations

Soil structure and drainage degradation are serious threats to farming and the environment in Scotland. Incentives and education could improve soil structure of many farms. Less autumn/winter traffic, more organic matter incorporation and avoiding root crops on vulnerable soils are potential mitigation practices. Farm specific surveys and management plans should be implemented in areas identified at being at risk. Some drains appear to be poorly functioning, but only cursory evidence is provided in this report, so greater monitoring is needed before deciding on action.

Moreover, a broader evidence base, backed with more quantitative data such as hydraulic conductivity, would greatly benefit environmental monitoring in Scotland. A major outcome from this project was the training of non-experts in assessing soil structure in the field, to assist with such monitoring.

Contents

Study Aims

CREW project CRW2014/3 'Effect of Soil Structure and Field Drainage on Water Quality and Flood Risk' provides a broad assessment of the state of soil structure and drainage on commercial farms in 4 selected catchments during autumn/winter 2015/2016. We describe the policy implications of the findings. Similar UK studies are used to discuss our results.
This project was commissioned by SEPA and addresses its Land Protection objective "make links between soil management and water protection measures to ensure maximum benefit for both soil/land and water quality" (SEPA, 2015). It also begins to address a need identified in the Supporting Material of the Scottish Soil Framework Directive (Scottish Government, 2008) to assess soil compaction in the field to assess its occurrence in Scotland and its effect on soil functions, and similar desires in the EU Soil Framework Directive (Loj, 2009).

Study Drivers

The maintenance of soil structure and functional field drainage has a large impact on runoff, water storage and potentially water quality. Appendix 1 provides a detailed review of government reports and scientific studies on this topic. Scotland's climate, machinery traffic and livestock trampling on agricultural soils, could make it very vulnerable the impacts of degraded soil structure and field drainage. Surface monitoring of soil properties by SEPA Catchment Coordinators, especially in winter months, has identified areas of standing water and evidence of runoff that could affect water quality. Farmers identified drainage and soil compaction as the greatest threats that soils face in Scotland (Munday, 2013). In a study linking water quality and soil degradation, Posthumus et al. (2011) found that farmers welcomed research that improved understanding, and suggested that locally tailored regulations and voluntary schemes would be very effective at protecting both waters and soils. This is reflected in the spending of over £2.6 million in crop levies paid to the Agriculture Horticulture Development Board on soil management research. Degraded soil or field drainage also has implications to the Water Framework Directive (WFD). This requires the sustainable use of water, including decreased pollution.

Data integrating field drainage, soil structure degradation and water quality are scarce in Scotland. This has been emphasised in numerous reports, including the supporting material used to develop the Scottish Soils Framework Directive (Scottish Government, 2009) and the State of Scotland Soil report (Dobbie et al., 2011). Recent desk studies commissioned via CREW that gathered data on agricultural drainage and its impact on flood risk in Scotland also identify a lack of available data (Lilly et al., 2012).

There is wider UK evidence of widespread soil structural degradation associated with cropping practice (Palmer and Smith, 2013), and increasing debate amongst hydrologists linking soil structural degradation and flood risk (Holman et al., 2003; O'Connell et al., 2007). These studies also link poorer drainage to overland flow and water quality, which has been the subject of far greater research.

CRW2014/3 'Effect of Soil Structure and Field Drainage on Water Quality and Flood Risk' therefore provided evidence for Scotland on the state of field drainage and soil structure in Scotland during the autumn and winter where the impacts on flooding and water quality can be greatest. It linked field survey data with existing modelling approaches that identify compaction and drainage risks.

The Study

Overview

We followed the pathway in Figure 1 to collect and interpret data on the extent and impact of soil structure and drainage degradation in Scotland. First we reviewed past literature to collate information on soil structure and drainage from previous work in Scotland and elsewhere. The review also verified our sampling approaches. We then identified sampling locations, with the intention of covering 120 fields across 4 catchments. A steering group provided a long-list of catchments to represent areas of concern for soil structure and drainage. Using soil mapping and modelling, we identified four catchments (and several reserve catchments) that provided geographic spread, a range of soil types and different vulnerabilities to soil compaction. Sampling locations were divided between catchments with about 30 each (27 in the Coyle, 32 in the East Pow, 30 in the south Esk and 31 in the Ugie Catchments.), with farmers contacted to access fields and start questionnaires on their cropping practices and drainage systems.

Field surveying commenced in October 2015. It used the Visual Evaluation of Soil Structure (VESS) (Ball et al., 2007) and Visual

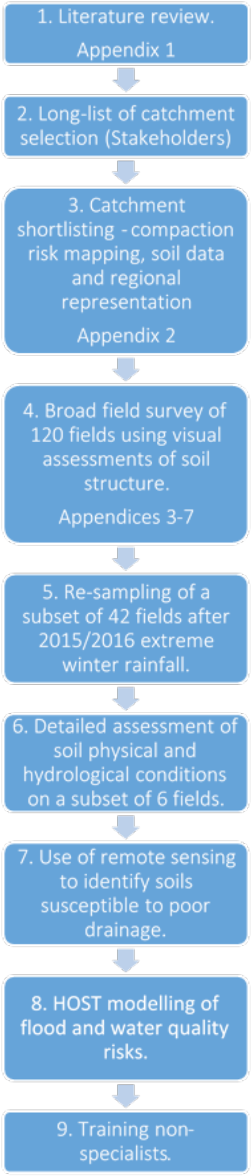


Figure 1 – Research pathway to assess soil structure and drainage conditions and impacts for Scotland. Details of some steps can be found in the Appendices, as indicated above.

Evaluation of Subsoil Structure (SubVESS) (Ball et al. 2015) to assess the condition of the soil structure. VESS and SubVESS have benefits of being standardised internationally and being quick to teach. A major outcome of this project is training of non-specialists to assess soil structural condition.
Winter 2015/2016 had the greatest winter precipitation in Scotland on record, so we extended the project by resampling 42 fields to assess whether periods of prolonged wetting exacerbated soil structural degradation and drainage problems.

More detailed soil hydrological measurements were made in a subset of the farms where VESS and SubVESS data were collected. Troughs were installed to collect run-off water which was subsequently measured for sediment and nutrient content and the volume of run-off was quantified. At the same locations, intact soil cores were taken to measure pore structure.
An additional component of the project was an exploratory study into using remote sensing to identify poorly drained soils.

Catchment Selection

A detailed description of catchment selection is provided in Appendix 2, with an overview provided here. The first part of the work was to review a selection of catchments proposed by the Stakeholder group. These were:

1. Cessnock, Ayrshire
2. Coyle, Ayrshire
3. East Pow, Perthshire
4. Eddleston, Borders
5. Glazert, East Dunbartonshire
6. Loch Leven, Fife
7. Lunan, Angus
8. South Esk, Angus
9. Ugie, Aberdeenshire
10. Carse of Stirling, Stirlingshire
11. Nith, Dumfries
12. Tarland, Aberdeenshire

Selection was made using the following sequence of criteria:

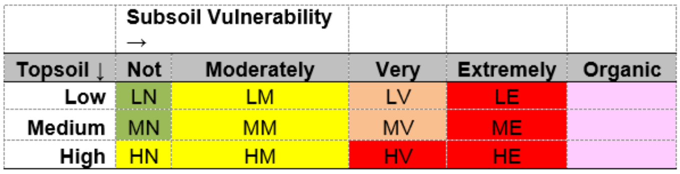
i. **Size**: Catchment size of less than 600 km2 with at least 25% arable land.

ii. **Compaction risk**: Compaction risk was modelled using the subsoil compaction vulnerability assessment (Jones et al., 2003) and topsoil compaction risk assessment (Ball, 1985 & 1986).   A traffic light system was used to identify areas that were highly susceptible to both topsoil and subsoil compaction (shown as red and amber in Figure 2). Any catchments with a combined amber and red compaction vulnerability with less 25% of the land area were identified and eliminated as they would not provide an adequate spread of predicted behaviour.

iii. **Drainage**: Catchments with large portion of soils with a standard percentage runoff (SPR) less than 25%, based on the HOST drainage classes (Boorman et al., 1995) were then eliminated as they would not be expected to generate problems with run-off.

iv. **Soils**: Catchments that contained a range of soils representative of agricultural land in Scotland (including Brown earth, Mineral gleys and Humus-iron podzols) were then identified for potential sampling.

v. **Geographic Spread**: From the list obtained after the above selection, we considered the geographic spread to encompass a range in land use and climate conditions in Scotland and also the feasibility of sampling by the team.



	Subsoil Vulnerability →				
Topsoil ↓	Not	Moderately	Very	Extremely	Organic
Low	LN	LM	LV	LE	
Medium	MN	MM	MV	ME	
High	HN	HM	HV	HE	

Figure 2 – Traffic light system from green to red to summarise the vulnerability of soil to compaction. Organic soils were not considered in compaction risk modelling.

The four catchments selected for detailed study were: Coyle, East Pow, South Esk and Ugie, with the sampling locations shown in Figure 3. The range of soil types in each catchment is shown in Figure 4.

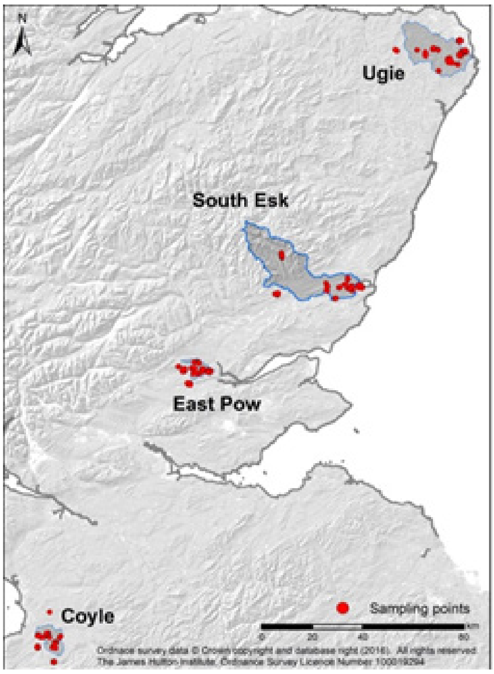


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Figure 3 – Location of the four catchments sampled during this project and specific sampling locations. Symbols in red indicate sampling locations

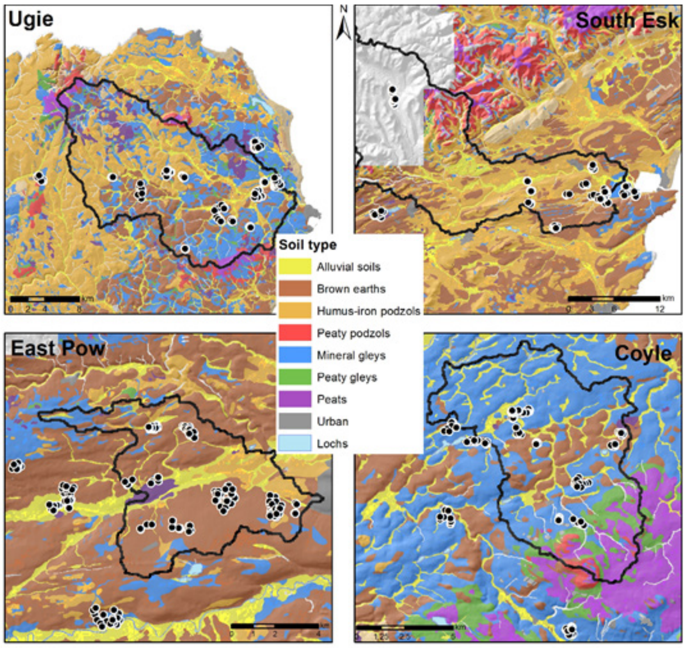

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Figure 4 – Distribution of soil types (major soil subgroups) across the catchments.

Field Sampling Approach

In each field, VESS and SubVESS assessments were conducted at 3 locations within the operational (cultivated) area, at the edges of fields where traffic was less and in heavily trafficked areas such as gates and turning circles (9 locations in total). A schematic of the typical sampling locations for a given field is shown in Figure 5. VESS is assessed by digging out a spade depth of soil (20-30 cm depth from surface) and assigning a score of between 1-5 based on the soil aggregate structure, including the presence of roots and ease of breakage of individual aggregates (see key provided in Appendix 3a). A score of 1 indicates excellent soil structure, whereas 5 indicates severely degraded soil structure. The score is based on the soil aggregate structure, including the presence of roots and ease at which individual aggregates can be prised apart.

The SubVESS assessment is made by further digging to about 20-50 cm depth and obtaining an intact sample of the subsoil. The assessment is also based on similar principals to VESS, but has slightly different criteria for assigning a score (see Appendix 3b).

Evidence of structural degradation of the surface soil (compaction, erosion, capping etc. Figure 6) was recorded at the same time as the VESS and SubVESS assessments. Information on recent weather, soil drainage, soil plasticity and agricultural practices (livestock, tillage, crops) was also recorded on a standard sampling template as shown in Appendix 4.

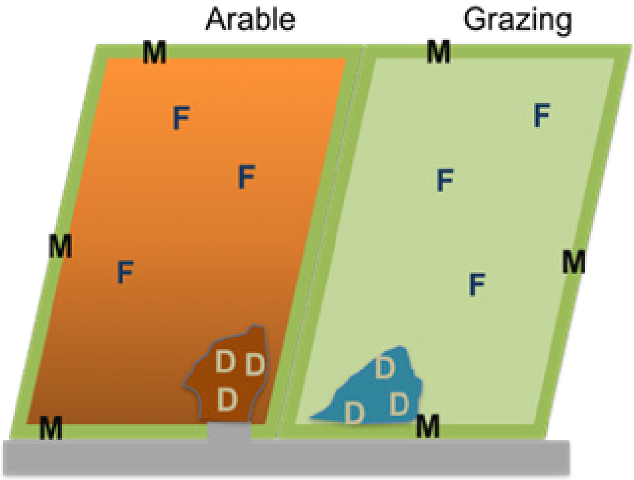


Figure 5 – Sampling locations in a typical Arable or Grazing field. The symbols refer to F – within the operation field, D – areas of heavy traffic that are visibly degraded on the surface, and M – less trafficked regions at the field margin. We refer to these areas as In '*Field*', '*Margin*' and '*Damaged*', respectively in the remainder of the report.

Figure 6 – Evidence of structural degradation of the surface soil [a].Poached topsoil [b] Topsoil erosion [c] Waterlogging [d] slaked topsoil

Visual Evaluation of Soil Structure

VESS and SubVESS were assessed in a total of 831 different sampling locations across the four catchments, providing the most widespread assessment of soil structure that has been conducted in Scotland for several decades. The sampling approaches, originating from SRUC (Ball et al., 2007 & 2015), proved to be rapid, reproducible, robust and easy to learn. Although winter deployment was challenging, reliable measurements could be obtained.

The frequency distribution VESS and SubVESS assessments for all point samples are presented in Figure 7. It was encouraging to find good soil structure for about 58% of topsoils (VESS scores of 1 or 2) and 67% of subsoils (SubVESS scores of 1 or 2) within the 533 in-field sampling locations operational fields.

However, we found severe soil structural degradation in 18% of topsoils (VESS scores of 4 or 5) and 9% of subsoils (SubVESS scores of 4 or 5) from within 533 '*In Field*' sampling locations. At the untrafficked field edges ('*Margins*') only 5% of topsoils and 3% of subsoils were severely degraded, giving evidence of soil structural degradation induced by farming practice. As expected, areas that were identified as '*Damaged*' from a surface inspection had a much greater frequency of poor VESS scores. '*Damaged*' areas also had more than double the proportion of poor SubVESS scores compared to '*In Field*' locations, indicating a link between surface damage and subsoil compaction. However, the proportions were much less than for VESS, with 62% of areas that are '*Damaged*' at the surface having good subsoil structural quality (SubVESS scores of 1 or 2). It is essential to dig deep and survey to truly assess subsoil compaction. Although the proportion of sites with subsoil compaction appear small, the damage is very difficult to rectify and results in localised problems with drainage and crop productivity.

The distribution of topsoil VESS scores was similar between catchments. In each catchment between 15 and 21% of the '*In Field*' topsoils assessed were severely degraded (VESS scores of 4 or 5), whereas between 48 and 63% of '*In Field*' topsoils showed good structure. In the Ugie catchment 22% of the sampled subsoils were severely degraded (sub-VESS scores of 4 or 5), whereas in the Coyle, South Esk and East Pow, less than 10% of the subsoils assessed showed severe structural degradation.

The '*In Field*' results show degraded topsoil structure where root crops have been grown, with 49% of these topsoils having VESS scores of 4 or 5 (Figure 8). However, the majority of subsoils where root crops had been grown (81%) showed good subsoil structure (VESS scores of 1 or 2). In grasslands 63% of topsoils and 73% of subsoils assessed had VESS scores of 1 or 2 (Figure 8). Graphs showing differences by crop type in VESS and SubVESS scores in '*Damaged*' areas and the '*Margins*' are shown in Appendix 5.

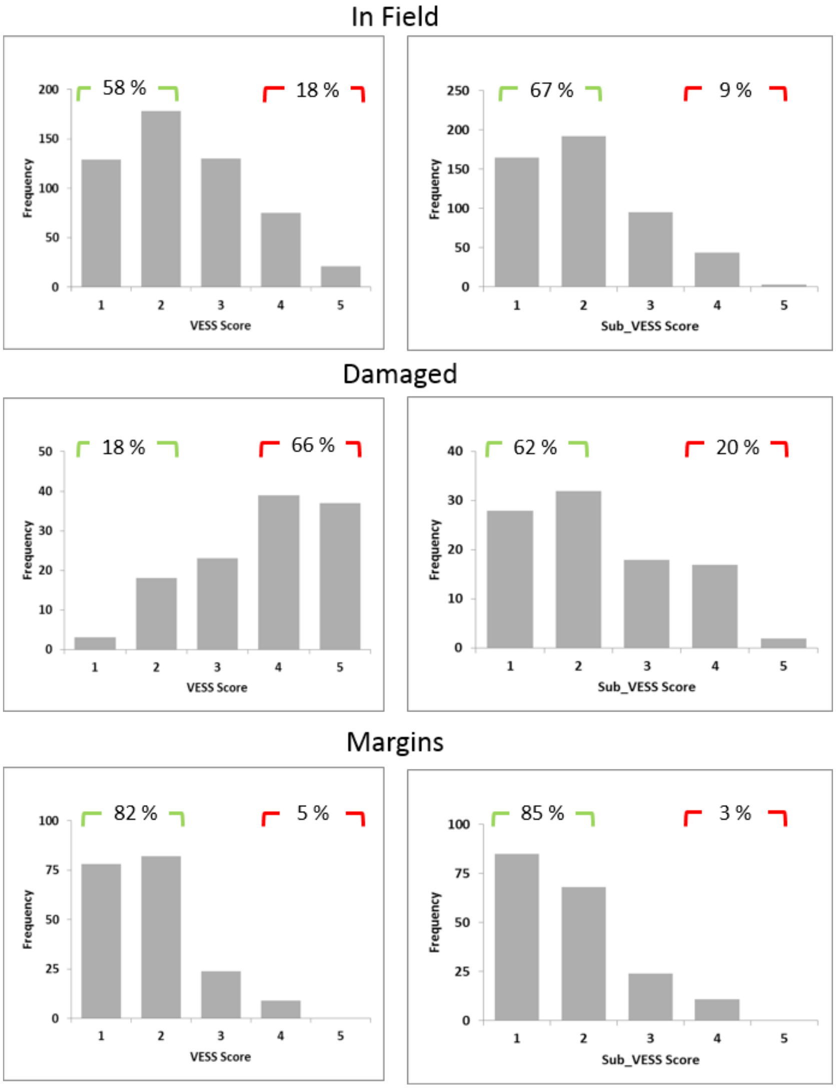


Figure 7 – Frequency distribution of the VESS and SubVESS scores for '*In-Field*' (Top), '*Damaged*' (Middle) and '*Margins*' (Bottom). VESS and SubVESS ≤ 2 indicates good structural condition, whereas ≥ 4 indicates severe degradation.

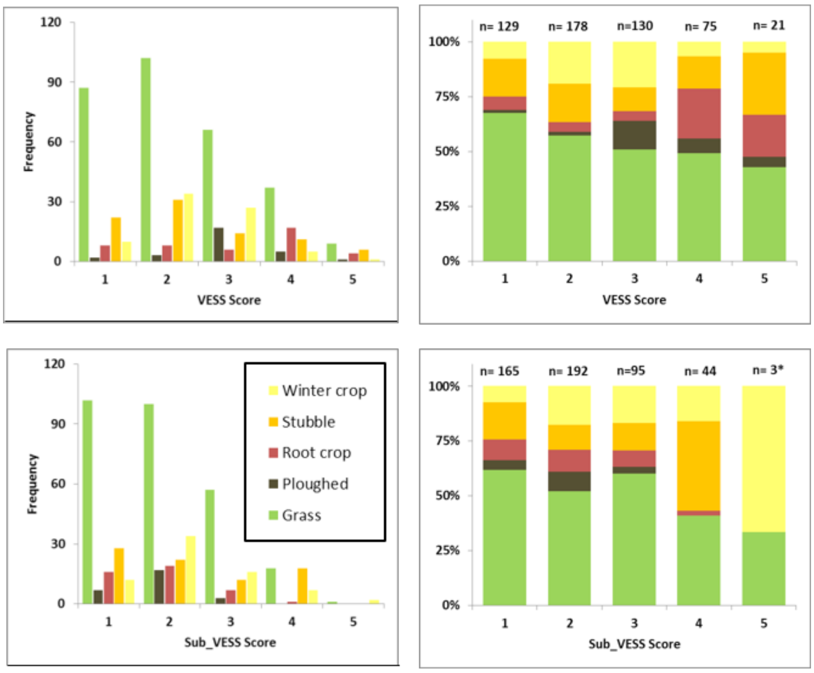


Figure 8 – VESS and SubVESS as affected by crop type in winter months. Only '*In Field*' data are shown (See Appendix 5 for other data). '*In Field*' refers to the main, productive area of fields. In the proportion graphs on the right, n is the number of locations where a measurement was made.

Expected trends in soil structure were found between soil types (Figure 9). Freely drained Podzols and Brown earths that are commonly associated with Scotland's best agricultural land had proportionally better soil structure than imperfectly or poorly drained soils, especially the Noncalcareous (mineral) gleys. In the subsoil, however, links between soil structure and soil type were less evident.

Next we considered how predictions of soil compaction risk (Figure 2) related to the actual soil structure assessment done on the ground (Figure 10). If the models are effective, a greater proportion of poor topsoil or subsoil structure scores would be expected for soils predicted to have a high compaction vulnerability. For topsoils, there are more with poor topsoil structure (VESS scores of 4 or 5) in higher risk soils but soils with good soil structure (VESS scores of 1 or 2) are spread across modelled risk classes (Figure 10). For subsoil compaction the trends are even less clear. For '*In Field*' regions there appears to be little relationship between predicted subsoil compaction risk and the SubVESS score measured in the field. The modelling predicts the risk of subsoil compaction rather than its occurrence, so machinery history or good farm practice may have allowed some extremely vulnerable soils to retain good soil structure. In the '*Damaged*' regions of fields, soils predicted to be extremely vulnerable to subsoil compaction had a greater occurrence of poor subsoil structure quality (SubVESS scores of 4 or 5).

Although these findings suggest the models go some way at predicting soil compaction risk, more information on soil management history and improved understanding of soil mechanical damage would be needed to improve reliability.

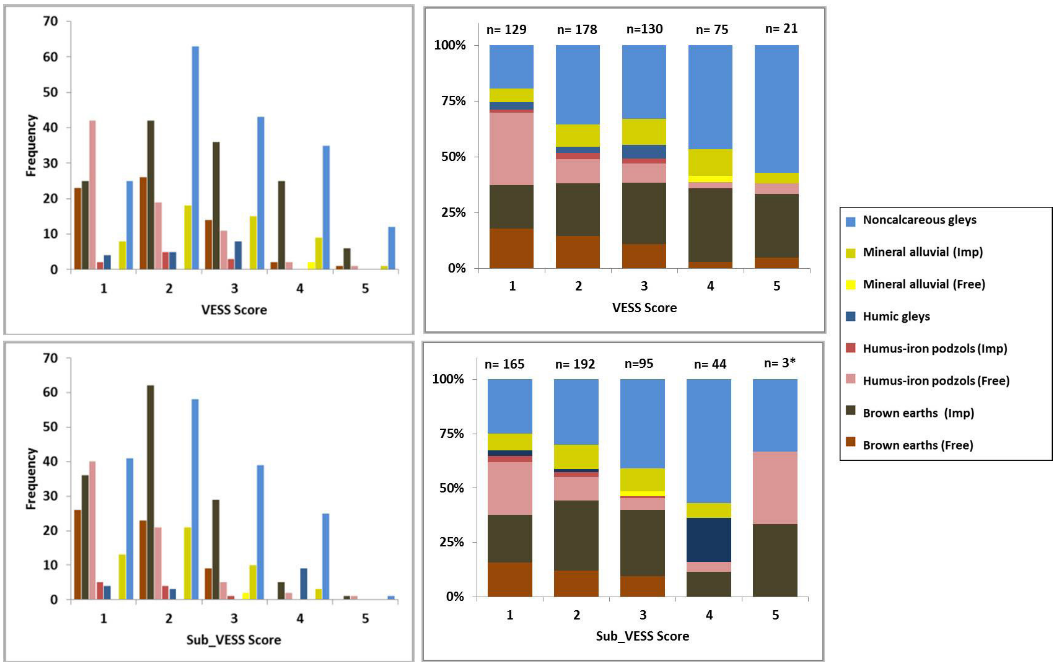


Figure 9 – VESS and SubVESS as affected by soil type in winter months. Only '*In Field*' data are shown (See Appendix 5 for other data). '*In Field*' refers to the main, productive area of fields. In the proportion graphs on the right, n is the number of locations where a measurement was made.

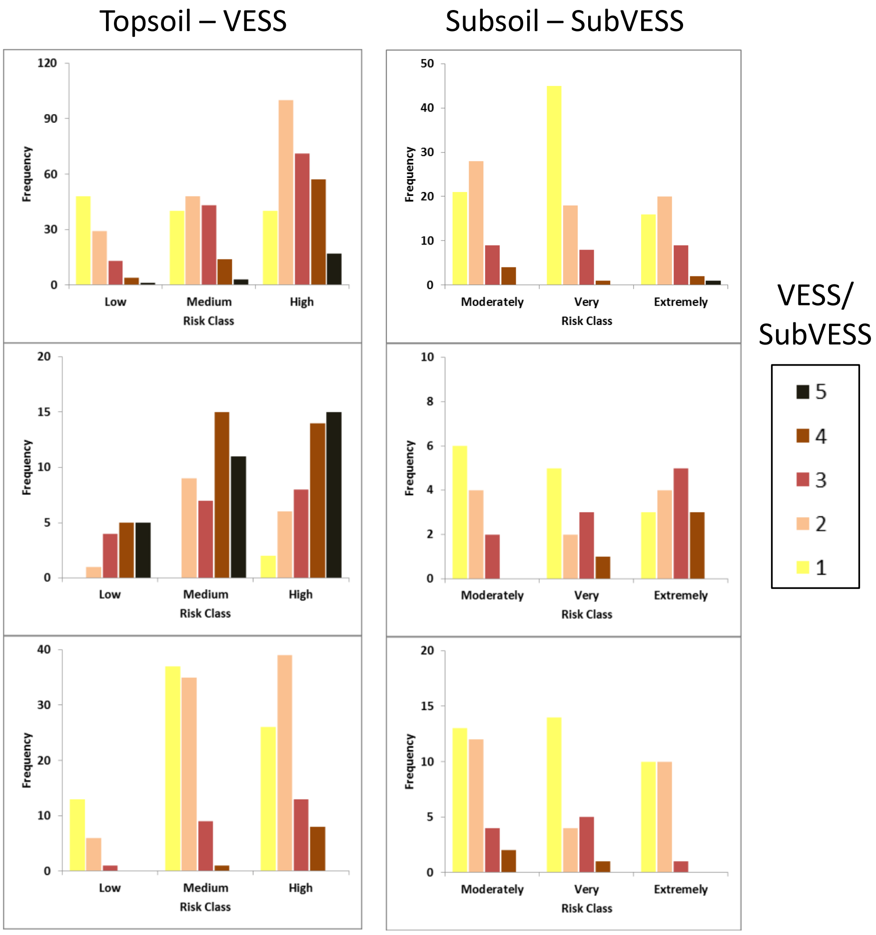


Figure 10 – Proportion of VESS (left) and SubVESS (right) falling under different topsoil and subsoil compaction risk classes, respectively. Each row of graphs corresponds to '*In Field*' (Top), '*Damaged*' (Middle) and '*Margins*' (Bottom). Figure 2 describes the risk classes.

Resampling of Soil Structure: Before and After Historically Unprecedented Rainfall

Scotland experienced its wettest ever winter in 2015/2016, with an average rainfall of 756 mm in December, January and February. Widespread flooding occurred and many agricultural fields remained flooded or water-logged for extended periods. As we had sampled a number of fields prior to this rainfall, it provided an opportunity to resample a subset of 42 of these fields to assess any changes in topsoil physical structure due to the high rainfall.

From the data presented in Figure 11, it is evident that the prolonged and intensive rainfall had a negative impact on soil physical structure. There was a 35% drop in sites with good topsoil structure (VESS of 1 or 2) for '*In Field*' regions. In '*Damaged*' areas of field good topsoil structure was rarely found and the severe rainfall resulted in a 46% increase in topsoils with poor structure (VESS of 4 or 5) or waterlogging that prevented resampling.

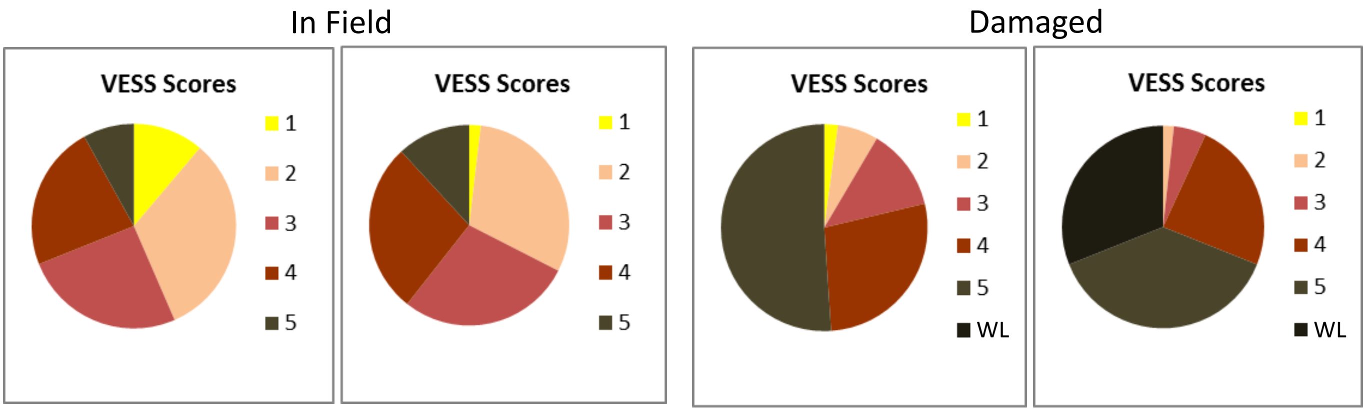


Figure 11 – Visual Evaluation of Soil Structure (VESS) based on 42 sites sampled before and after Scotland's historic rainfall event of December/January of 2015/2016. 1-5 refers to the VESS score with '*In Field*' shown at the left and '*Damaged*' areas of the field at the right. Waterlogged fields after the rainfall are shown as WL.

Run-off, Water Quality and Soil Physical Conditions

In a total of six fields, greater assessment of run-off, water quality and soil physical conditions, was carried out. These consisted of three fields in each of East Pow and South Esk catchments. Within each of these catchments, field selection was based on topsoil and/or subsoil compaction risk. We also selected paired fields that had visually different surface damage, which we assumed to be due to the agricultural practices employed. Sampling locations in each of the six fields followed the strategy used for VESS that is illustrated in Figure 5. This incorporated at least 3 locations each within the operational field (cultivated), '*Damaged*' areas and '*Margins*', with a further 6 locations focussing on turning circles and tramlines making a total of 15 locations. At all locations, intact soil cores were taken at two depths to measure bulk density, macroporosity, hydraulic conductivity and water content at field capacity.

In addition to these detailed soil measurements, 5 unbounded Gerlach runoff troughs were installed in each field. These captured runoff and soil loss for a range of slope lengths/contributing areas. The troughs were connected to a sealed tank to store water and sediment runoff. Runoff water samples were analysed to assess the likely impact on water quality based on their physio-chemical characteristics and compared with source soils (Table 1). Precipitation was measured with rain gauges located near to the Gerlach troughs.

Runoff samples and source soil samples were analysed for Nitrate (NO3), Ammonium (NH4) and total Phosphorus (P). We also multiplied the water samples by the amount of water collected to show the actual runoff per 1m plot. Figure 12 shows the amount of runoff/rainfall for all runoff plots. As expected we collected the most runoff from heavy trafficked areas (TL, D) and less from '*In Field*' and field margin locations. Surprisingly we collected runoff from field 2 and three in East Pow, this was due to flooding events and standing water at the bottom of a slope by the River Pow. Runoff coefficient measurements differed from February to March for infield operation areas as only two locations in South Esk collected any rainfall. Crop growth had a direct impact on runoff collection; the plots which had collected runoff had limited crop cover whereas plots with no runoff collection had recent crop growth.

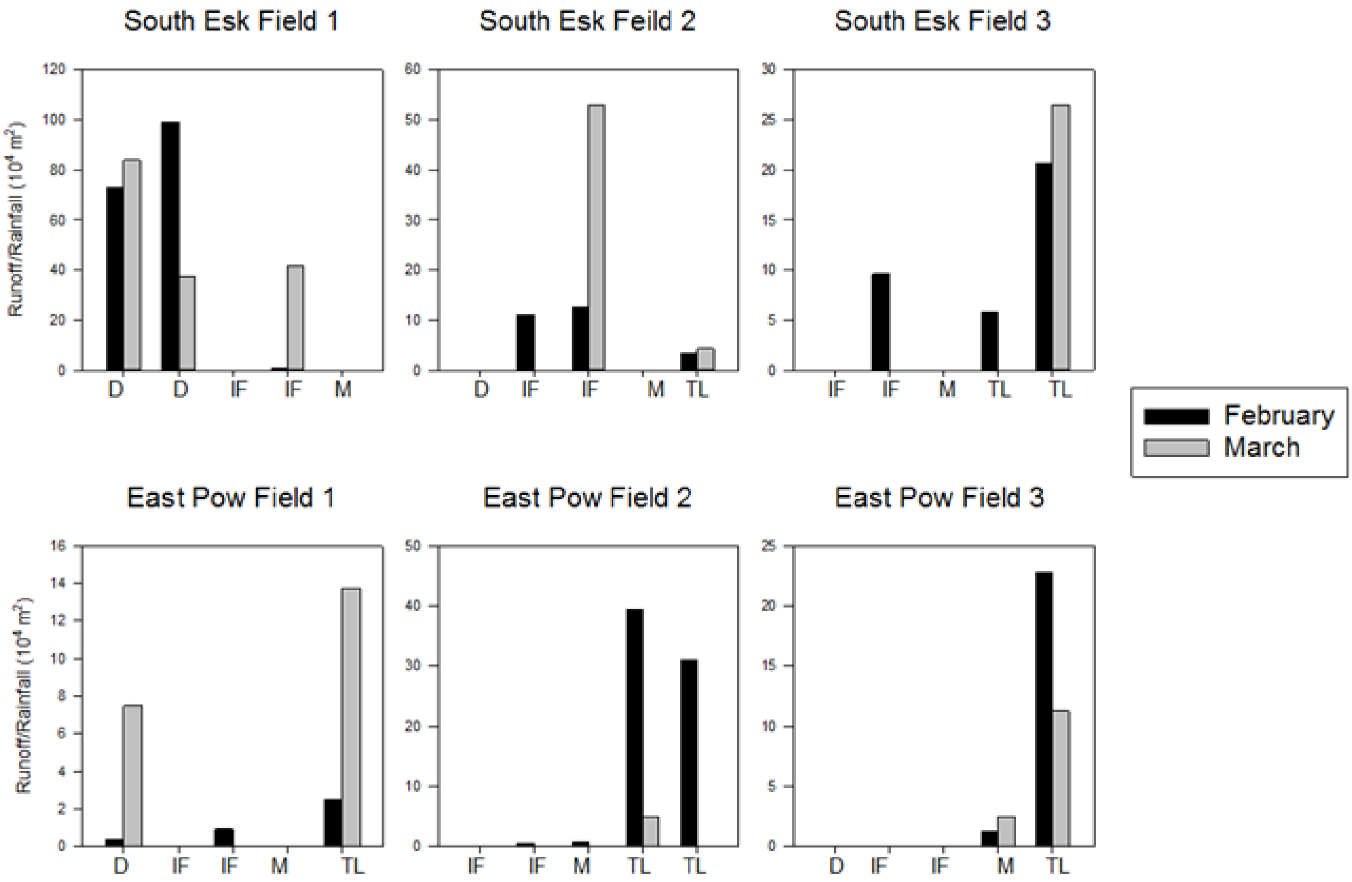


Figure 12 – Runoff/Rainfall as collected by unbounded Gerlach troughs in East Pow and South Esk catchments in different locations within a field based on the level of traffic. The symbols refer to IF – within the operation field, D – areas of heavy traffic or that are visibly degraded on the surface, M – less trafficked regions at the field margin, and TL as any areas with heavy traffic in main tramlines.

		South Esk (13mm cumulative rainfall)								East Pow (23mm cumulative rainfall)							
		In Field		**Margin**		**Tramline**		**Damaged**		**In Field**		**Margin**		**Tramline**		**Damaged**	
NO_3 (mg/l)	Soil (mg/l)	0.0098	0.0027	0.0019	0.0004	*	*	0.0079	0.0014	0.0141	0.0054	0.0091	0.003	*	*	0.0139	0.0034
	Runoff (mg/l)	1.007	0.173	*	*	0.685	0.271	0.719	0.489	1.069	0.346	0.114	*	0.367	0.284	1.2	*
	Runoff (mg/m trough)	0.616	0.435	*	*	0.493	0.139	0.6069	0.0863	0.369	0.114	0.0404	*	0.0906	0.0589	0.26	*
NH_4 (mg/l)	Soil (mg/l)	0.0107	0.013	0.0068	0.0012	*	*	0.0061	0.0014	0.0088	0.0019	0.0076	0.0014	*	*	0.0053	0.0009
	Runoff (mg/l)	0.64	0.224	0.962	0.329	0.493	0.139	1.418	1.194	0.3466	0.0054	0.3545	*	0.533	0.309	0.21	*
	Runoff (mg/m trough)	0.87	0.418	*	*	1.7	1.32	17.3	11.8	0.0586	0.0153	0.1028	*	3.52	2.32	0.02	*
P (mg/l)	Soil (mg/l)	0.0099	0.0015	0.0081	0.0009	*	*	0.0089	0.0008	0.0096	0.0007	0.0075	0.0012	*	*	0.0093	0.0008
	Runoff (mg/l)	0.1329	0.0367	*	*	0.1557	0.0323	0.2014	0.0624	0.1311	0.0571	0.1094	*	0.0917	0.0337	0.05	*
	Runoff (mg/m trough)	0.1259	0.0408	*	*	0.0923	0.0344	0.1143	0.0536	0.16	0.106	0.0125	*	0.0267	0.0147	0.06	*

Table 1 - Nitrate (NO3), Ammonium (NH4) and total Phosphorus (P) of source soil, runoff and runoff per m of field, collected in each catchment for each location. S.E. Standard error * No data collected – No available standard error.

We used saturated hydraulic conductivity as a measure of infiltration at the selected locations of the field (Figure 13). Results from both catchments indicate clearly that infiltration is fastest within the operational areas of the field (ANOVA, $p<0.01$). This corresponds with findings from Gerlach trough measurements as there is less runoff in most operational and margin samples (Figure 11).

To assess the physio-chemical properties of the soil we compared hydraulic conductivity to percent carbon (%C), porosity and bulk density.

Surprisingly no significant relationship was shown between '*In Field*', '*Margins*' and '*Damaged*' areas of fields.

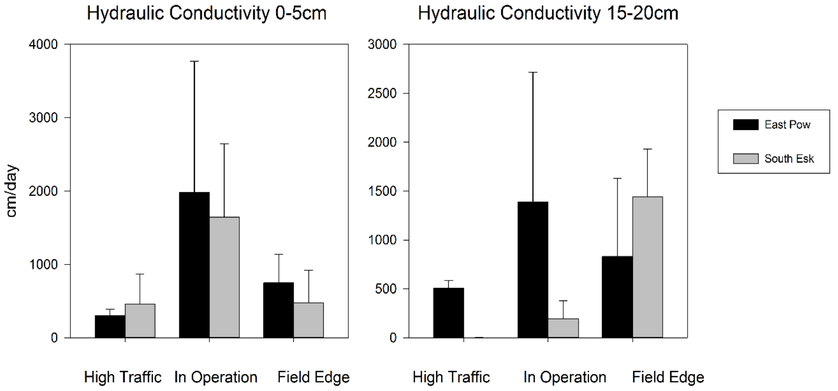


Figure 13 – Saturated hydraulic conductivities of intact core samples from both catchments.

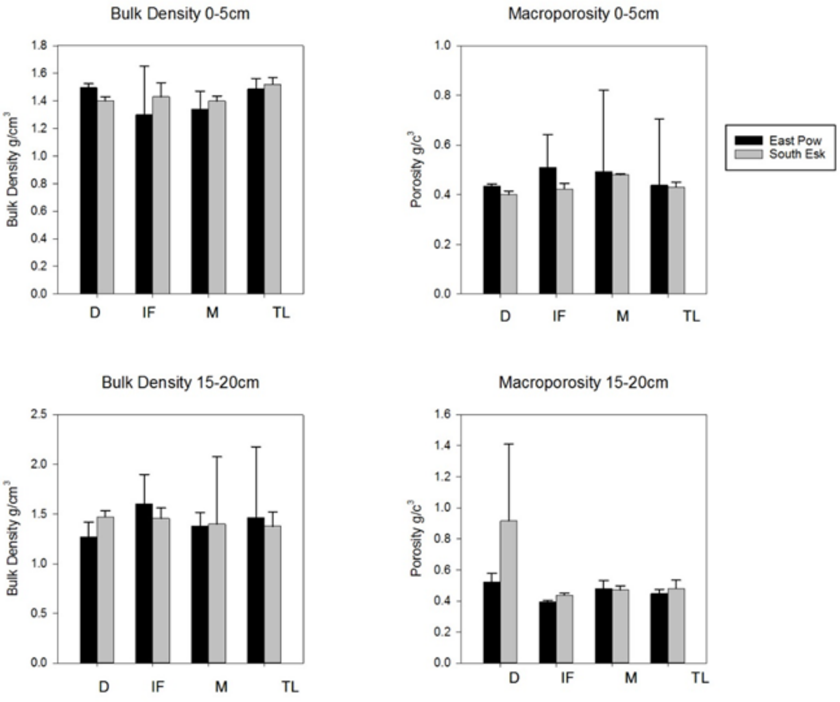


Figure 14 – Soil Physical properties of dry bulk density and soil macroporosity from intact soil cores from both catchments. The symbols refer to IF – within the operation field, D – areas of heavy traffic or that are visibly degraded on the surface, M – less trafficked regions at the field margin, and TL as any areas with heavy traffic on tramlines.

Field Drainage Assessment

We also assessed the current state of agricultural drainage in the 120 fields surveyed. This examined sediment build-up and blocking of drains where they were visible in drainage ditches (Appendix 6). The photographs in Figure 15 illustrate differences found in the visual assessments of drainage outfalls, with the results summarised in Table 2. We also provided a questionnaire to farmers on their field drainage systems (Appendix 7), which we aimed to complete during the field visit. A total of 28 drainage questionnaires were completed by farmers and surveyors, results are shown in Table 3. A farm report template is given in Appendix 8.

Results suggest that 39% of the 120 agricultural fields assessed had clear and free flowing field drains, 20% were slow running and blocked with sediment and 6% were blocked. Overall, of the 124 fields assessed we did not identify any agricultural drainage in 44 fields (35%).

We found that the questionnaires varied in response for views on agricultural drainage (Table 4), although 80% of applicable questionnaires revealed that agricultural drainage was the major restriction on yield. Of the applicable questionnaires 52% of farmers see field drainage as degraded and suggested that the solution was ditch dredging.

Catchment	Clear/Free flowing	Slow/ Sediment	Blocked	Not Found
Coyle	13	5	1	9
East Pow	14	8	2	8
South Esk	9	6	1	16
Ugie	12	6	3	11

Table 2 – Visual assessment of agricultural drains in ditches per catchment.

a. Free flowing drain with ochre

b. Blocked drain

c. Slow/not flowing drain with sediment

d. Blocked drain with vegetation and ochre.

Figure 15 – Visual assessment of agricultural drains in ditches.

Systems/ Maintenance	Yes	No	Not Applicable
Systems;			
Ditches	28		
Sub Surface drainage pipes	25	3	
Mole drains	4	24	
Other		28	
Maintenance;			
Jet washing	21		2
Subsoiling	6		3
Unblocking	24	3	1

Table 3 – Farmer questionnaire answers to agricultural drainage per farm

	Yes	No	Not Applicable
Is current land drainage the major restriction on yield?	20	5	3
Is more drainage needed?	16	12	
Are you willing to upgrade current drainage?	20	6	2
Do you view the current drainage as degraded?	14	13	1
Do you view drainage as a major expense?	22	4	2
Is Ochre a problem?	12	16	

Table 4 – Farmer questionnaire answers to drainage systems and maintenance used on farm. See Appendix 7 for questionnaire.

In this survey we categorised field drainage as ditches and burns, subsurface drainage pipes, mole drains and any artificial drainage systems used in farm management (Table 3). The questionnaire we provided farmers assessed the field drainage used by each farm, although when identifying the need for upgrading and current state of drainage the questionnaire did not directly associate this with type of drainage. This may have misidentified the difference in maintenance and providing a crossover between current state of drains and maintenance.

Visual assessments of drainage outlets of each field showed a broad range of conditions and mainly free flowing drains. As drainage was mainly assessed in wet weather conditions the likelihood of finding outlets was increased, however as shown in Figure 15 blocked drains were difficult to identify. While 59% of the fields visually assessed showed functioning drainage outlets, there is a limitation to the study as drains may have been missed.

The drainage survey provided an overview on the state of drains in Scotland, however a more rigorous assessment of drainage is needed to have a less arbitrary data set. Further work comparing soil drainage classes with farmer questionnaire answers is needed to see if those who view drainage as degraded is linked with soil type.

HOST Modelling of Run-off

In 2002, Holman et al. published a report on the impact of agricultural soil conditions on the autumn 2000 floods in England. In the report, they modified the HOST (Hydrology of Soil Types) classification (Boorman et al., 1995) Standard Percentage Runoff (SPR) coefficients to estimate the additional runoff likely from degraded soils compared to those with good soil structure. SPR is a hydrological index of the soils response to rainfall and can be used to predict flood flows as it quantifies the rapid response of the soil to a rainfall event. Holman et al. (2002) identified two main scenarios, 'conservative' where they modified the SPR by up to 10% of the existing value (i.e. a SPR of 10% would become a SPR of 11%) and an 'extreme' where the current SPR for any soil would be doubled. They also commented that there was no quantitative data linking soil degradation to stream response.

There are two main components of HOST that are likely to be influenced by soil structural degradation; porosity as measured by soil moisture retention curves, bulk density, infiltration or hydraulic conductivity and depth to a slowly permeably layer. The porosity measurements are important distinguishing criteria for only a few HOST classes found in Scotland (HOST 9, 10, 18, 19, and 22) while the depth to a slowly permeable layer is a key distinguishing factor in the classification.

Rather than making arbitrary adjustments to the SPR values, it was decided to base the changes on measured or observed soil properties collected during the field component of the project. Initially, the role of soil porosity was investigated, however, there were too few measurements to extrapolate to all the soils in each of the 4 catchments though there was a general decrease in porosity and conductivity between the '*In Field*' operational areas and the '*Damaged*' parts of the field. Since it is also likely that only soils in HOST classes 9, 10 and 18 are likely to be cultivated and that HOST classes 9 and 10 are perhaps a special case in terms of runoff due to their proximity to rivers (they are predominantly alluvial soils), it was felt that a better approach would be to assess the potential impact where the soils had an observed cultivation pan and so where the effective depth to a slowly permeably layer had been altered. The depth to a slowly permeably layer determines the water storage capacity of the soil as well as the rate of infiltration. It was felt that soils that had developed a pan at depths ≤ 40cm could be (temporarily) reclassified as HOST class 24 for the purposes of this assessment of potential increased runoff as they would now meet the criteria for the HOST class in terms of specified flow pathways.

The SPR of each of the four catchments was determined by the method set out in the HOST report (Boorman et al. 1985) by multiplying the proportional area of each HOST class in the catchment by the SPR assigned to that HOST class. The SPR values determined for the catchments are shown in Table 5.

The method to assess the additional runoff caused by soil degradation takes account of the observed data where only a proportion of the soils in a catchment had a pan rather than the blanket increase in runoff used by Holman et al. (2002). It then reassigns soils to a HOST class that reflects the flow pathways and storage capacity of a soil with a cultivation induced slowly permeable layer (plough pan). The number of soil profiles that had a cultivation pan at a depth of ≤ 40cm was determined for each of the 4 catchments investigated. These soils were grouped by HOST class as derived from a 1:25 000 scale map of HOST classes and the proportion of the soils in each HOST class that had an observed cultivation pan determined. The catchment SPR was then recalculated by assigning these soils with a pan to HOST 24 (where their current SPR was less than that of HOST 24, i.e., <39.7%) and adjusting the area of the catchment with HOST class 24 upwards in line with the proportions of soil with pans.

Catchment	SPR from HOST (%)	SPR from modified HOST (%)
Coyle	40.77	41.03
East Pow	35.40	36.52
South Esk	38.74	39.93
Ugie	32.5	35.04

Table 5 – Calculated catchment Standard Percentage Runoff (SPR) using the HOST classification and the change in SPR after reassigning HOST class based on the proportion of permeable soils with a plough pan.

It is clear that not all HOST classes were sampled in the field campaign so there was no information on whether these soils had developed a plough pan or not. In the case where there was no data none of the soils were reassigned to HOST class 24. In addition some soils sampled, those in HOST classes 12, 15, 26 and 29, all had SPR values greater than HOST class 24 and so the soils were not reassigned to HOST class 24. HOST classes 16, 18 and 24 represent decreasing depths to a slowly permeable layer and should be reflected in increasing SPR values, however, HOST 24 has a SPR value less than that of HOST 18. The reason for this was unclear at the time of developing the HOST classification, however, it means that HOST class 18 was also not reassigned the HOST class 24 SPR value even if the soil had a cultivation pan.

The results for the Coyle show that there is little change in the SPR for the catchment after reassigning '*Damaged*' soils to HOST class 24 and this probably reflects the low proportion of soils (16%) in the catchment with SPR values less than HOST class 24. The East Pow showed a greater change in predicted runoff compared to the Coyle (increase of 1.12%) which reflected the greater proportion of both permeable soils (28%) and those that had observed cultivation pans (8%). However, there was a large area of HOST class 18 in the catchment, of which 30% of the soil profiles sampled in this HOST class had an observed cultivation pan. If this proportion of the soils were '*Damaged*' there is likely to be an additional increase the SPR of the catchment.

The increase in the SPR of the South Esk catchment was slightly greater than that of the East Pow at 1.19% and again reflected the greater proportion of permeable soils that are more prone to compaction (subsoils of slowly permeable soils such as HOST class 24 are already naturally compact) at around 40% of the catchment. Again, like the East Pow, there is a large proportion of HOST class 18 in the catchment (almost 35%).

The Ugie showed the greatest increase in catchment SPR of the four catchments studied (increase of 2.52%) and had the greatest proportion of permeable soils that were reassigned to HOST class 24.

In summary, we adopted a slightly different approach to Holman et al. (2002) in calculating the potential changes in catchment runoff index. However, we used the observed data to apply a proportional reclassification of certain HOST classes to HOST class 24, which is defined as having a slowly permeable layer with 40 cm of the soil surface. These revised figures can be used to assess the potential runoff for any rainfall event. We haven't taken into account the position of the '*Damaged*' soils in relation to the river network which may have an influence on the speed at which a river rises, instead the proportion of '*Damaged*' soils were evenly distributed throughout the catchment. In addition there is the potential that '*Damaged*' soils in HOST class 18 will have a greater SPR value and this would further increase the SPR mainly for the East Pow and South Esk catchments. As part of the work to identify drainage condition on agricultural soils in four catchments across Scotland, there was interest in finding out if remote sensing could provide useful data for detection of poor soil drainage due to compromised drainage systems. Further details can be found in Appendix 9.

Conclusions and Recommendations

This initial survey of soil structure, drainage and water quality of over 120 commercial farm fields identified severe challenges on about 18% of the studied locations. Using HOST modelling, soil structural degradation was enhancing run-off, supporting a need to conduct more detailed research on this topic to understand the potential impacts on flooding. Root crops were associated with more soil structural degradation than other crops. A judicious choice of cropping practice to suit particular soils provides a potential management solution that could be adopted to protect soils and water in Scotland. The study spanned the greatest winter precipitation event in Scotland's history. The large amount of rainfall was found to exacerbate soil structural degradation over time. Field drainage was found to require maintenance in many locations, which also presents a challenge to managing soils and water in Scotland.

We propose more extensive surveying of soil drainage across Scotland as the current study only provided a cursory examination. Farmers are clearly interested in understanding the quality of drainage on their farm, and recognise it as a serious threat to farming in Scotland. There was encouraging agreement between compaction risk mapping and VESS scores measured in the field. However, improved modelling of soil structure degradation, coupled with mapping, could identify areas of Scotland where policy intervention to manage soils could have the greatest impact.

Government policies could be developed to tackle the evidence of soil structure and drain degradation observed in our study. Land management choices should avoid the growing of root crops on sensitive soils. Existing advice to farmers to avoid traffic by machinery or livestock when soils are wet, as supported by GAEC, needs greater encouragement as soil structural damage is still occurring. Policy makers also need to consider the potential damage to subsoils by heavy machinery. Our finding that 9% of subsoils had poor structure based on a visual assay is highly significant. Subsoil structural damage is difficult to rectify and may have wide ranging environmental impacts.

References

Ball, B. C., Batey, T. & Munkholm, L. J. 2007. Field assessment of soil structural quality - a development of the Peerlkamp test. Soil Use and Management 23: 329-337.

Ball, B. C., Batey, T., Munkholm, L. J., Guimaraes, R. M. L., Boizard, H., McKenzie, D. C., Peigne, J., Tormena, C. A. & Hargreaves, P. 2015. The numeric visual evaluation of subsoil structure (SubVESS) under agricultural production. Soil & Tillage Research 148: 85-96.

Ball, B.C. (Compiler) 1985. Cultivation requirements for Winter barley. SAC/MISR/SIAE publication 154. Scottish Agricultural Colleges. Edinburgh.

Ball, B.C. 1986. Provisional land grouping for selection of cultivation requirements for Winter barley in Scotland. Soil and Tillage Research, 7: 7-18.

Boorman, D.B., Hollis. J.M. & Lilly, A. 1995. Hydrology of soil types: a hydrologically based classification of the soils of the United Kingdom. Institute of Hydrology Report No. 126.

Dobbie, K.E, Bruneau, P.M.C & Towers, W. (eds.). 2011. The State of Scotland's Soil. Natural Scotland, www.sepa.org.uk/land/land_publications.aspx

Holman, I. P., Hllis, J.M., Bramley, M.E. and Thompson, T.R.E. 2003. The contribution of soil structural degradation to catchment flooding: a preliminary investigation of the 2000 floods in England and Wales. Hydrology and Earth System Sciences 7, 754-765.

Jones, R. J. A., Spoor, G. & Thomasson, A. J. 2003. Vulnerability of subsoils in Europe to compaction: a preliminary analysis. Soil and Tillage Research, 73: 131-143.

Lilly, A., Baggaley, N., Rees, B., Topp, K., Dickson, I. and Elrick, G. 2012. Report on agricultural drainage and greenhouse abatment in Scotland. Prepared on behalf of ClimateXChange. Scottish Government. 41 pp.

Loj, G. 2009. The new thematic strategy for protecting soils in europe. Desertification and Risk Analysis Using High and Medium Resolution Satellite Data: 83-88.

Munday, R. 2013. Farmers' views on research needs in soil science in Scotland. BSc Honours Project. The University of Aberdeen. 64 pp.

O'Connell, E., Ewen, J., O'Donnell, G. & Quinn, P. 2007. Is there a link between agricultural land-use management and flooding? Hydrology and Earth System Sciences 11(1): 96-107.

Palmer, R.C. and Smith, R.P. 2013. Soil structural degradation in SW England and its impact on surface-water runoff generation. Soil Use and Management, 29, 567-575.

Posthumus, H., Deeks, L. K., Fenn, I. & Rickson, R. J. 2011. Soil conservation in two english catchments: linking soil management with policies. Land Degradation & Development 22(1): 97-110.

Scottish Government. 2009. The Scottish Soil Framework Directive. Scottish Government, Edinburgh, UK, 63 pp.

SEPA. 2015. SEPA position statement on land protection (Reference EP 054). http://www.sepa.org.uk/media/159201/ep-054_position_statement_on_land_protection.pdf. Accessed 18 May, 2015.

Appendix 1 - Review of Past Literature and Selection of Sampling Methods

Field Drainage:

Over 60% of the UK agricultural land area is drained (Wiskow & van der Ploeg, 2003) to improve hydrological conditions for crop production and extend the number of days that fields can be accessed by machinery or livestock. In soils that are wet in spring, subsoil drainage allows for greater root exploration at depth (Goss et al., 1984), so if drought occurs in summer the crop is more resilient (Bengough et al., 2011). Drainage can convert lower quality, poorly drained soils, into highly productive agricultural land. In a study on the interaction between soil series and crop yields, natural drainage conditions identified by soil surveys had little effect, but it was felt that this was due to the installation of drainage systems that greatly improved soils (Weir et al., 1984). Effective drainage of grazing systems was found by Tyson et al. (1992) to increase plant dry matter yield and livestock weight gain by over 10%. Early drainage systems installed at the time of the agricultural revolution over 100 years ago are thought to have improved crop yields by more than 10% on water-logged soils (Brunt, 2004). In addition, there are knock-on benefits to soil carbon storage by draining soils susceptible to water-logging (van Wesemael et al., 2010).

Despite widespread drainage of agricultural land in Scotland, a desk study by Lilly et al. (2012) reported about half of cultivated land area suffers some degree of seasonal water-logging. Although they felt that drainage systems were sub-optimal, with poor recent investment, it was still thought that they were in good to moderate condition. However, they recognised that data were sparse and called for a national survey of field drainage, similar to surveys in England and Wales. A Defra funded study on field drainage identified a peak in the installation of new or reconditioned drainage systems in the 1980s for England and Wales, followed by a sharp decline in the 1990s when grant aid to install drainage was removed (ADAS, 2002). This report recognised a dearth of data on drainage maintenance, relying instead on the assumption that drainage systems greater than 40 years old would exhibit ‘less than effective drainage’. Drainage can degrade from physical damage, in-filling by soil and plant roots (Figure A1:1) or less effective water transport through soil due to structural degradation. A large area of drainage was installed prior to the early 1960s, with evidence from drainage contractors suggesting limited maintenance of plastic pipe systems and a greater reliance on secondary drainage through moling or subsoiling. A more recent Nuffield Farming Scholarships Trust report by Burtonshaw (2013) engaged directly with drainage contractors and found that investment in UK farming continued to be poor, particularly in comparison to other countries. He argued that GPS yield mapping had driven drainage investment in North America and identified secondary benefits to the environment by installing systems like bioreactors to decrease fertiliser movement.

Drainage is installed to increase agricultural yield, but it has impacts to flooding and water quality. Blanc et al. (2012) produced a literature review for CREW on drainage impacts to flood risk. From studies on test catchments, hydrologically isolated plots and modelling, they concluded drainage impacts to flood risk were site specific, depending on soil properties and wider hydrological conditions. In some instances drainage exacerbates peak flow events, whereas in others the peak flow events are mediated. If drainage is impeded by poor soil physical conditions that decrease water transport rates to drains, water-logging and overland flow increase, leading to greater peak flow and water quality degradation (Wheater and Evans, 2009).

Soil Structural Degradation

In the hydrological science literature there is increasing debate about the link between flood risk, soil structural degradation (Holman et al., 2003) and land use (O’Connell et al., 2007). However, these studies, like those on agricultural drainage just described, were cautious about making direct links because the evidence base was limited. In the wake of the 2014 floods in Southwest England, a timely publication by Palmer & Smith (2013) was seized by journalists (Monbiot, 2014) and hydrologists as supporting evidence that soil structure degradation leads to flooding. From a survey of 3243 sites across Southwest England, Palmer & Smith (2013) found that 38% had soil structure so degraded that it produced visible evidence of poor water infiltration and overland flow in winter. For arable crops that are harvested late, such as maize, 75% of the sites were found to have degraded soil structure. In an earlier study by Holman et al. (2002), that surveyed winter soil structural condition in the Severn, Yorkshire Ouse and of the rivers Uck and Bourne in the south-east of England, a more conservative 20-30% of sites had ‘enhanced soil degradation’.

For late harvested crops, however, the incidence was 55%. Photographs from their report illustrating soil structural degradation are shown in Figure A1:2. By combining their new data with the National Soil Map of England and Wales, a simple model (HOST) predicted increases in runoff water reaching rivers of 0.5 to 12%. Although this represents a significant increase, which suggests greater flood risk, Holman et al. (2002) were cautious about inferring too much from this desk-based study.

Figure A1:1 – Agricultural drains can be blocked by a mix of roots and soil. Source: Leuty (2012).

Figure A1:2 - Holman et al. (2002) observed (from top left clockwise) compacted topsoil, hoof damage with standing water, surface slaking and surface capping indicating soil structural degradation in four UK catchments.

Newell Price et al. (2012) examined soil structural conditions in 300 grassland fields in England and Wales. From bulk density cores, they considered 16% of soils to be 'compacted' based on trigger values proposed by Merrington (2006). From a visual assessment of soil structure they found 8% of fields to be in poor condition and 54% in moderate condition. Although these findings are more favourable than Holman et al. (2002) or Palmer & Smith (2013), they still suggest soil physical degradation is widespread in UK grasslands. Newell Price et al. (2012) felt that the other studies may have been biased by focussing on flooding prone catchments. In upland soils in England and Wales, McHugh (2007) found that over a 3-4 year period that 52% of 139 sites had worsening erosion, mainly due to sheep grazing.

There is a potential that a vicious circle of continually degrading soil structure could result if drainage is impeded from either poorly functioning drains or soil structure. Figure A1:3 illustrates various processes that degrade soil structure. Soil compaction is likely to be an increasing problem in Scotland due to greater machinery weight and possibly an increase in erratic weather conditions that results '*In Field*' access in suboptimal conditions when soils are too wet (Dobie et al., 2011, Bradley et al., 2005). A recent study from Denmark concluded that soil compaction was the greatest threat to the functioning of Danish soils, including the capacity for soil to produce crops and buffer pollutants (Schjønning, 2009). Farmers invest considerably in mitigating compaction damage through subsoiling, although the effectiveness and economic value of this practice is debatable (Chamen et al., 2015), particularly in climates like Scotland where subsoiler implements can smear rather than fracture soils due to plasticity (Osullivan, 1992). Low ground pressure tyres, controlled traffic to dedicated tramlines, changes in tillage practice and more judicious timing of operations provide other options to avoid or mitigate arable soil compaction damage (Chamen et al., 2015). In grasslands, mechanical soil loosening can be performed with aerators, sward lifters and subsoilers, but only five experimental studies have evaluated the impacts in the UK (Bhogal et al., 2011). These studies found that mechanical loosening can improve the functioning of grasslands providing they are conducted in appropriate conditions. However, the improvements are short-lived due to recompaction.

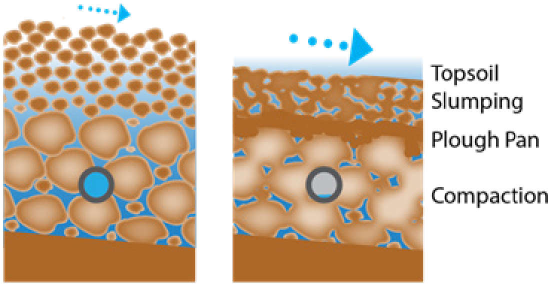


Figure A1:3 - The physical structure of soil can degrade through inter-linked processes of compaction, slumping and the effectiveness of artificial drainage.

Organic matter depletion also affects the susceptibility of soils to compaction as it provides natural springs that increase resilience to compression (Zhang et al., 2005) and improves structural stability by aggregating soil particles (Tisdall and Oades, 1982). In an assessment of over 100 arable fields in Scotland, 50% had less than 3% organic carbon, with 10% less than 1 % organic carbon (Valentine et al., 2012). Such small carbon levels can correspond to critical levels where soil structural stability declines drastically (Six et al., 2004), with each 1% drop in organic matter resulting in a 1-2% decline in soil porosity (Riley et al., 2008). Newell Price et al. (2012) found increased bulk density with declining organic matter. Organic matter also affects the the slumping of seedbeds (Hao et al., 2011) or loose soils left after root crop harvesting.

If drainage is impeded, wetter soils lead to greater slumping (Augeard et al., 2008) and surface sealing (Assouline and Mualem, 2001), which exacerbates overland flow and erosion. In a study of both surface sealing and coalescence of deeper soil, Bresson & Moran (2004) found that under prolonged wetting, coalescence was the dominant process affecting porosity and likely infiltration degradation. This means that field assessments of soil structural condition need to look beneath surface properties that are visible from very rapid assessments. Other research found that flooding a soil caused greater loss of soil porosity than introducing an equivalent amount of water through rainfall (Hao et al., 2011), which is a condition that would arise with poorly functioning drains. Initial tilth structure also has a large impact on sealing, slumping and erosion. Seventy years ago, Edie et al. (1946) reported a link between the fineness of tilth from cultivation and the propensity of soil erosion during flooding.

Water Quality Impacts

This project explores potential autumn and winter impacts from soil structure damage and agricultural drainage efficiency on water quality. A previous report to CREW (CREW, 2012) divided soil borne pollutants into autumn occurring pesticides, fertiliser, faecal compounds and dissolved carbon, and winter occurring suspended sediments, entrained phosphorus and particulate carbon. Pollutants enter freshwater from a wide range of agricultural uses, with arable inputs widely appreciated and recent research demonstrating significant potential inputs from lowland grasslands that are intensively managed for livestock production (Peukert et al., 2014). About 2/3 of surface waters in the UK do not comply with drinking water standards or good ecological status, with agriculture causing the greatest threat to compliance (McGonigle et al., 2012). Zhang et al. (2014) suggested that agriculture was responsible in 72% of sediment, 31% of phosphorus and 81% of nitrogen incidences of non-compliance with these standards in the UK. In order to decrease pollutant loads, land uses that cause problems need to be identified. Scotland has a large number of studies showing agriculture as a major contributor to pollutants (Dawson et al., 2012), but fewer studies drill down to specific agricultural land use impacts. At catchment scale, freshwater monitoring of pollutants may be at too coarse a resolution to identify impacts of specific agricultural land use and external environmental factors may influence measurements. For instance, a monitoring study of the Lunan catchment in NE Scotland, found that nitrogen inputs were linked to agricultural land use, but trends were not observed for sediments or phosphorus (Dunn et al., 2014). This study suggested smaller-scale monitoring that picks up field resolution inputs is required, which will be addressed to some extent in the current CREW study. In a recent review, Deasy et al. (2014) recommended field studies at farm and catchment scale over longer time scales to link land use with run-off and flood risk.

There are clear impacts of drainage and soil structure on freshwater quality. In moist temperature regions like Scotland, trampling damage by livestock decreases soil porosity and the risk of overland flow (Ball et al., 2012). Effective grazing rotations and limiting field access to the growing season, thereby avoiding autumn and winter trampling, can result in 3x greater water infiltration (Stavi et al., 2011). Livestock weight also has a large impact on the extent of damage, with heavier cattle, in comparison to lighter livestock, causing significant increases to soil penetration resistance (a measure of ease of plant root growth linked to soil compaction) (Herbin et al., 2011).

Bare, winter, arable soils are a major source of mobilised suspended solids that erode from soils to freshwater through runoff (Stevens et al., 2009). Autumn cultivation can increase erosion by 89% on highly erodible soils (Ulen et al., 2010), with tillage well recognised to influence the flow of nutrients and water (SEPA, 2002). Chambers and Garwood (2000) found that winter cereals, which are planted into freshly tilled autumn seedbeds, were associated with 80% of erosion events they monitored in a large-scale, 5 year, multiple catchment study. However, autumn cultivation can also greatly increase infiltration rates, apart from along tramlines which are a major source of sediments and phosphorus pollution to freshwater (Borresen and Uhlen, 1991). Specific mitigation options, such as the breaking up of tramlines or reduced tillage, can decrease pollutant loads by appreciable amounts (Deasy et al., 2009).

Assessing Soil Structural Condition and Water Quality

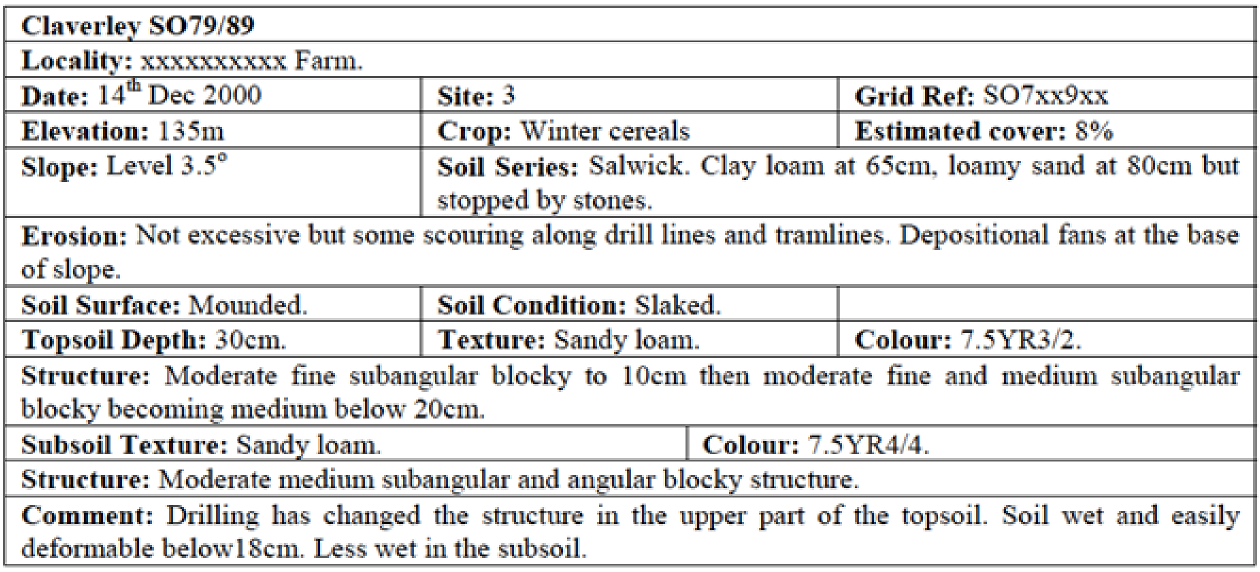
Field Assessment of Soil Structure

Field based soil structure assessments go back to early soil surveys, where the inherent shape of soil peds and drainage are integral to classification systems. Whilst these data have some use in upscaling predictions of soil hydrology, they were not developed to specifically characterise soil structural degradation. Numerous field survey methods have been developed to assess soil structure directly, based on the early visual assessment originally developed by Peerlkamp (1959) (Ball et al., 2007). Richard et al. (1999) used a larger scale trench sampling approach to characterise the heterogeneity of soil structure post tillage by exploring the prominence and location of clods and smaller aggregates in the soil. This assay compares wheelways to surrounding soils to assess cultivation efficiency and compaction damage. Later research by this team explored how this structure changes over time during the growing season (Roger-Estrade et al., 2004). An approach by Mueller et al. (2009) provides a detailed, hierarchical assessment of soil structure. A great benefit of the Richard et al. (1999) and Mueller et al. (2009) approaches is that they provide a large amount of information on the state of soil structure, but they are time consuming to conduct.

To enable a survey of many sites over a short time span, Palmer and Smith (2013) and Holman et al. (2002) used a more rapid assessment that incorporated a visual examination of surface soils for ponding, run-off and erosion in winter. A spade test allowed for soil structural degradation to be classified into numerous classes of severity. Soil structure was classified based on the degradation classes listed in Table A1:1. An example of a field observation report from Holman et al. (2002) is shown in Figure A2:4.

Class	Name	Description
S	Severe	Soil degradation generates sufficient enhanced runoff to cause widespread erosion that is not confined to wheelings / tramlines.
H	High, Extensive	Soil degradation generates enhanced runoff across whole field, where slopes allow
M	Moderate, Local	Soil degradation generates localised areas of enhanced runoff, where slopes allow
L	Low	Insignificant enhanced run-off generation

Table A1:1 - Soil degradation classes adopted by Holman et al. (2002).



Claverley SO79/89		
Locality: xxxxxxxxxx Farm.		
Date: 14th Dec 2000	**Site:** 3	**Grid Ref:** SO7xx9xx
Elevation: 135m	**Crop:** Winter cereals	**Estimated cover:** 8%
Slope: Level 3.5°	**Soil Series:** Salwick. Clay loam at 65cm, loamy sand at 80cm but stopped by stones.	
Erosion: Not excessive but some scouring along drill lines and tramlines. Depositional fans at the base of slope.		
Soil Surface: Mounded.	**Soil Condition:** Slaked.	
Topsoil Depth: 30cm.	**Texture:** Sandy loam.	**Colour:** 7.5YR3/2.
Structure: Moderate fine subangular blocky to 10cm then moderate fine and medium subangular blocky becoming medium below 20cm.		
Subsoil Texture: Sandy loam.	**Colour:** 7.5YR4/4.	
Structure: Moderate medium subangular and angular blocky structure.		
Comment: Drilling has changed the structure in the upper part of the topsoil. Soil wet and easily deformable below18cm. Less wet in the subsoil.		

Figure A1:4 - A field observation report by Holman et al. (2002).

The Palmer and Smith (2013) and Holman et al. (2002) methods are best employed by experienced soil surveyors because structural classes are not well characterised. Ball et al. (2007) developed the Visual Evaluation of Soil Structure, VESS, to provide a tool that could be used by either experienced soil surveyors or people with less experience working with soils in the field. Soil structure is assigned an Sq score ranging from 1-5 using a score card shown in Appendix 3. Soil is extracted to spade depth (20-30 cm), placed on a tray, and then distinct layers are assigned specific soil structure scores. The approach works very well in assessing soil conditions for crop growth and damage from machinery and livestock. VESS was developed first on Scottish soils and has since been applied to numerous soils internationally (Giarola et al., 2013). It is related to more quantitative measurements of soil physical structure, such as air permeability and bulk density (Guimaraes et al., 2013), so it is reliable as a field surveying approach. A similar approach to VESS, the Visual Assessment of Soil from New Zealand, was used in the grassland study of Newell Price et al. (2012).

Given the ease of use of VESS and its widespread deployment in the National Soil Inventory of Scotland resampling (NSIS2), this approach will be adopted in our study. We complement it with the recently developed Visual Evaluation of Subsoil Structure (SubVESS) (Ball et al., 2015). This focuses on the upper subsoil (>30 cm) that in arable soils is often just beneath the deepest depth where cultivation has occurred. In subsoils, the dissipation of stresses from traffic and natural soil restructuring processes (e.g. wetting and drying, bioturbation by roots and fauna) make subsoils particularly vulnerable to irrecoverable structural degradation (van den Akker, 2004). SubVESS resembles the VESS method, with scores based on visual porosity, strength, mottling, aggregate size and shape, and the proliferation of plant roots. In winter months when fields are wetter, deploying SubVESS was challenging, but the standard approach of extracting an intact block of soil with a spade was successfully employed.

We complemented the VESS and SubVESS assessments of soil structure with a visual examination of surface water, erosion, wheelway and poaching damage, following the approach of Holman et al. (2002). Any measured increased runoff due to compaction or structural degradation was used to modify the HOST runoff parameter for individual soil series (Palmer & Smith, 2013) and scaled for the catchment to estimate the potential increased runoff for each catchment.

Quantitative Measurements of Soil Physical Condition and Functioning

The visual approaches just described provide rapid surveying methods that are suitable for the CREW project specification. Detailed assessments of the functioning of agricultural drainage, soil structural degradation and the associated impacts to water quality would require a substantial investment, but we adopted a limited approach on a subset of 6 fields in each of two catchments. This provided initial data to cross-check HOST and compaction modelling at catchment level, and to assess the robustness of visual methods. Detailed assessments of the effectiveness of agricultural drains on farms cannot be conducted as these would require very deep sampling to inspect drains.

Runoff, Erosion and Water Quality

Assessing run-off and erosion accurately requires in-field measurements. Bounded, hydrologically isolated plots are commonly used '*In Field*' experiments, but they are not suitable to commercial farms (Withers et al., 2006). More feasible, albeit less accurate, measurements intercept run-off water as it travels downslope to allow quantification of the total volume of water and concentrations of entrained sediments, nutrients and agrochemicals (Stevens et al., 2009). Water is intercepted in a trough that can be constructed from gutter pipe available from a building merchant (Hudson, 1993) and then collected in water containers that are drained periodically after rainfall events. In our study these will be installed at 3 locations in fields and where possible compared to 3 locations at field boundaries that have not been cultivated for some time. The collected run-off will be measured for volume, total solids and nutrients. A rainfall gauge will measure the amount of precipitation between samplings.

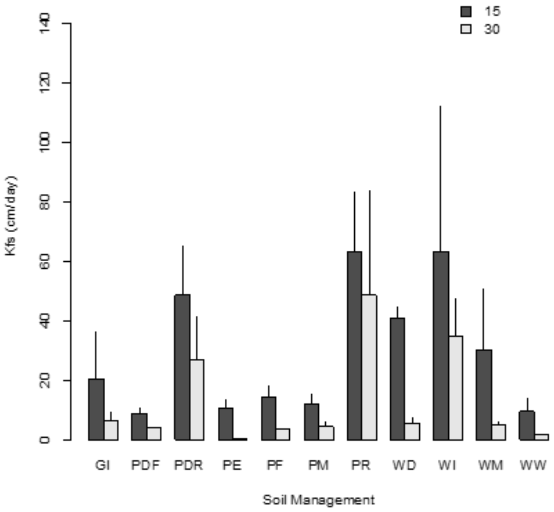


Figure A1:5 - A preliminary trial of the Guelph Permeameter in South Esk did not detect differences '*In Field*' hydraulic conductivity, Kfs, between contrasting soil treatments including wheelways (WW) and in-field (WI) for winter wheat. Three replicates were measured per treatment.

Soil Water Infiltration

The capacity of soil to transport water is defined by its hydraulic conductivity, which can be measured in the field with infiltrometers or in the laboratory using intact soil cores extracted from the field. '*In Field*' measurements have the advantage of minimising disturbance to the soil and sampling over a larger surface area than is possible with cores in the laboratory. However, in wet winter sampling, the measurements may be difficult to conduct. In May we trialled field infiltrometer measurements at South Esk Farms for this study, and found that the measurements were too variable to detect differences between wheelways and surrounding soil (Figure A1:5). A Guelph Permeameter was used and sources of error were attributed to smearing of the borehole formed to make measurements, wind affecting the Mariott bottle system used to establish a constant head and inherent field variability in soil properties. Each test takes about 30 minutes so greater replication over the 3 used in this study would not be feasible. Minidisk infiltrometers were also tested and the results were poorer, as expected given the smaller area of soil measured (Jirku et al., 2013). Given the challenge of deploying field infiltrometers, more controlled testing with extracted soil cores will be used (Gribb et al., 2004). However, cores will be 250 cm^3 (compared to 100 cm^3 for standard cores) and we use the new UMS KSAT system http://www.ums-muc.de/en/products/soil_laboratory/ksat.html.

References

ADAS (2002). Development of a database of agricultural drainage. Final project report to Defra. Project Code: ES0111.

Assouline, S. & Mualem, Y. (2001). Soil seal formation and its effect on infiltration: Uniform versus nonuniform seal approximation. Water Resources Research 37(2): 297-305.

Augeard, B., Bresson, L. M., Assouline, S., Kao, C. & Vauclin, M. (2008). Dynamics of soil surface bulk density: Role of water table elevation and rainfall duration. Soil Science Society of America Journal 72(2): 412-423.

Ball, B. C., Batey, T. & Munkholm, L. J. (2007). Field assessment of soil structural quality - a development of the Peerlkamp test. Soil Use and Management 23(4): 329-337.

Ball, B. C., Batey, T., Munkholm, L. J., Guimaraes, R. M. L., Boizard, H., McKenzie, D. C., Peigne, J., Tormena, C. A. & Hargreaves, P. (2015). The numeric visual evaluation of subsoil structure (SubVESS) under agricultural production. Soil & Tillage Research 148: 85-96.

Ball, B. C., Cameron, K. C., Di, H. J. & Moore, S. (2012). Effects of trampling of a wet dairy pasture soil on soil porosity and on mitigation of nitrous oxide emissions by a nitrification inhibitor, dicyandiamide. Soil Use and Management 28(2): 194-201.

Ball, B.C. (Compiler) (1985). Cultivation requirements for Winter barley. SAC/MISR/SIAE publication 154. Scottish Agricultural Colleges. Edinburgh.

Ball, B.C. 1986. Provisional land grouping for selection of cultivation requirements for Winter barley in Scotland. Soil and Tillage Research, 7: 7-18.

Bengough, A. G., McKenzie, B. M., Hallett, P. D. & Valentine, T. A. (2011). Root elongation, water stress, and mechanical impedance: a review of limiting stresses and beneficial root tip traits. Journal Of Experimental Botany 62(1): 59-68.

Bhogal, A., Bentley, C., Newell Price, P. & Chambers, B. (2011). The alleviation of grassland compaction by mechanical soil loosening. Report to Defra. BD5001: Characterisation of soil structural degradation under grassland and development of measures to ameliorate its impact on biodiversity and other soil functions. 27 pp.

Blanc, J., Arthur, S., Wright, G. & Beevers, L. (2012). Natural flood management (NFM) knowledge system: Part 3 - The effect of land drainage on flood risk and farming practice. Report for Scotland's Centre of Expertise for Waters, CREW. 34 pp.

Boorman, D.B., Hollis. J.M. & Lilly, A. (1995). Hydrology of soil types: a hydrologically based classification of the soils of the United Kingdom. Institute of Hydrology Report No. 126.

Borresen, T. & Uhlen, G. (1991). Soil erosion and phosphorus losses in winter surface runoff in field lysimeters at Aas Norway 1989-1990. Norsk Landbruksforsking 5(1): 47-54.

Bradley, I., Moffat, A., Vanguelova, E., Fallon, P. and Harris, J. (2005). Impacts of climate change on soil functions. Defra project SP0358. 28 pp.

Bresson, L.M., Moran, C.J. (2003) Role of compaction versus aggregate disruption on slumping and shrinking of repacked hardsetting seedbeds. Soil Science 168, 585-594.

Brunt, L. (2004). Nature or nurture? Explaining English wheat yields in the Industrial Revolution, c. 1770. Journal of Economic History 64(1): 193-225.

Burtonshaw, R. (2013). Land Drainage and its role in farming's future. A Nuffield (UK) Farming Scholarships Trust Report. 37 pp.

Chambers, B. J. & Garwood, T. W. D. (2000). Monitoring of water erosion on arable farms in England and Wales. 1990–94. Soil Use and Management 16(2): 93-99.

Chamen, W. C. T., Moxey, A. P., Towers, W., Balana, B. & Hallett, P. D. (2015). Mitigating arable soil compaction: A review and analysis of available cost and benefit data. Soil and Tillage Research 146, Part A(0): 10-25.

CREW (2012). The potential risks to water quality from diffuse pollution driven by future land use and climate change. Report for Scotland's Centre of Expertise for Waters, CREW. 28 pp.

Dawson, J. J. C., Adhikari, Y. R., Soulsby, C. & Stutter, M. I. (2012). The biogeochemical reactivity of suspended particulate matter at nested sites in the Dee basin, NE Scotland. Science of the Total Environment 434: 159-170.

Deasy, C., Quinton, J. N., Silgram, M., Bailey, A. P., Jackson, B. & Stevens, C. J. (2009). Mitigation Options for Sediment and Phosphorus Loss from Winter-sown Arable Crops. Journal of Environmental Quality 38(5): 2121-2130.

Deasy, C., Titman, A. & Quinton, J. N. (2014). Measurement of flood peak effects as a result of soil and land management, with focus on experimental issues and scale. Journal of Environmental Management 132: 304-312.

Dobbie, K.E, Bruneau, P.M.C & Towers, W. (eds.) (2011). The State of Scotland's Soil. Natural Scotland, www.sepa.org.uk/land/land_publications.aspx

Dunn, S. M., Sample, J., Potts, J., Abel, C., Cook, Y., Taylor, C. & Vinten, A. J. A. (2014). Recent trends in water quality in an agricultural catchment in Eastern Scotland: elucidating the roles of hydrology and land use. Environmental Science-Processes & Impacts 16(7): 1659-1675.

Edie, E. G., Seelye, C. J. & Raeside, J. D. (1946). Notes on the Canterbury floods of February, 1945. New Zealand Jour Sci and Tech 27 B((5)): 406-420.

Giarola, N. F. B., da Silva, A. P., Tormena, C. A., Guimaraes, R. M. L. & Ball, B. C. (2013). On the Visual Evaluation of Soil Structure: The Brazilian experience in Oxisols under no-tillage. Soil & Tillage Research 127: 60-64.

Goss, M. J., Howse, K. R., Vaughanwilliams, J. M., Ward, M. A. & Jenkins, W. (1984). Water-use by winter-wheat as affected by soil-managemenT. Journal of Agricultural Science 103(AUG): 189-199.

Gribb, M. M., Kodesova, R. & Ordway, S. E. (2004). Comparison of soil hydraulic property measurement methods. Journal of Geotechnical and Geoenvironmental Engineering 130(10): 1084-1095.

Guimaraes, R. M. L., Ball, B. C., Tormena, C. A., Giarola, N. F. B. & da Silva, A. P. (2013). Relating visual evaluation of soil structure to other physical properties in soils of contrasting texture and management. Soil & Tillage Research 127: 92-99.

Hao, H., Hartmann, C., Apichart, J., Siwaporn, S., Promsakha, S., Richard, G., Bruand, A. & Dexter, A. R. (2011). Slumping dynamics in tilled sandy soils under natural rainfall and experimental flooding. Soil & Tillage Research 114(1): 9-17.

Herbin, T., Hennessy, D., Richards, K. G., Piwowarczyk, A., Murphy, J. J. & Holden, N. M. (2011). The effects of dairy cow weight on selected soil physical properties indicative of compaction. Soil Use and Management 27(1): 36-44.

Holman, I. P., et al. (2003). "The contribution of soil structural degradation to catchment flooding: a preliminary investigation of the 2000 floods in England and Wales." Hydrology and Earth System Sciences 7, 754-765.

Holman, I.P., Hollis, J.M. and Thompson, T.R.E. (2002). Impact of agricultural soil conditions on floods – Autumn 2000. R&D Technical Report W5B-026/TR. Defra/Environment Agency Flood and Coastal Defence R&D Programme. Environment Agency, 30 p.

Hudson, N.W. (1993). Field measurement of soil erosion and runoff. FAO Soils Bulletin 68, Food and Agriculture Organization of the United Nations, Rome. 139 pp

Jirku, V., Kodesova, R., Nikodem, A., Muhlhanselova, M. & Zigova, A. (2013). Temporal variability of structure and hydraulic properties of topsoil of three soil types. Geoderma 204: 43-58.

Jones, R. J. A., Spoor, G. & Thomasson, A. J. (2003). Vulnerability of subsoils in Europe to compaction: a preliminary analysis. Soil and Tillage Research, 73: 131-143.

Leuty, T. (2012). Farm tile drains and tree roots. Ontario Ministry of Agriculture, Food and Rural Affairs Factsheet. Guelph, Canada.

Lilly, A., Baggaley, N., Rees, B., Topp, K., Dickson, I. and Elrick, G. (2012). Report on agricultural drainage and greenhouse abatment in Scotland. Prepared on behalf of ClimateXChange. Scottish Government. 41 pp.

Loj, G. (2009). The new thematic strategy for protecting soils in Europe. Desertification and Risk Analysis Using High and Medium Resolution Satellite Data: 83-88.

McGonigle, D. F., Harris, R. C., McCamphill, C., Kirk, S., Dils, R., Macdonald, J. & Bailey, S. (2012). Towards a more strategic approach to research to support catchment-based policy approaches to mitigate agricultural water pollution: A UK case-study. Environmental Science & Policy 24: 4-14.

McHugh, M. (2007). Short-term changes in upland soil erosion in England and Wales: 1999 to 2002. Geomorphology 86(1-2): 204-213.

Merrington, G. (2006). The Development and Use of Soil Quality Indicators for Assessing the Role of Soil in Environmental Interactions. Environment Agency Science Report SC030265, 241pp.

Monbiot, G. 2014. How we ended up paying farmers to flood our homes. The Guardian. 18 February, 2014.

Mueller, L., Kay, B. D., Hu, C. S., Li, Y., Schindler, U., Behrendt, A., Shepherd, T. G. & Ball, B. C. (2009). Visual assessment of soil structure: Evaluation of methodologies on sites in Canada, China and Germany Part I: Comparing visual methods and linking them with soil physical data and grain yield of cereals. Soil & Tillage Research 103(1): 178-187.

Munday, R. (2013). Farmers' views on research needs in soil science in Scotland. BSc Honours Project. The University of Aberdeen. 64 pp.

Newell Price, P., Chambers, B. and Whittingham, M. (2012). WP1 Characterisation of soil compaction under grassland. Grassland Soil Compaction Assessment – Stages 1 and 2. Report to Defra - BD5001: Characterisation of Soil Structural Degradation Under Grassland and Development of Measures to Ameliorate its Impact on Biodiversity and other Soil Functions. 96 pp.

O'Connell, E., Ewen, J., O'Donnell, G. & Quinn, P. (2007). Is there a link between agricultural land-use management and flooding? Hydrology and Earth System Sciences 11(1): 96-107.

Osullivan, M. F. (1992). Deep loosening of clay loam subsoil in a moist climate and some effects of traffic management. Soil Use and Management 8(2): 60-67.

Palmer, R.C. and Smith, R.P. 2013. Soil structural degradation in SW England and its impact on surface-water runoff generation. Soil Use and Management, 29, 567-575.

Peerlkamp, P.K. (1959). A visual method of soil structure evaluation. Meded. v.d. Landbouwhogeschool en Opzoekingsstations van de Staat te Gent. XXIV No. 24, pp. 216–221.

Peukert, S., Griffith, B. A., Murray, P. J., Macleod, C. J. A. & Brazier, R. E. (2014). Intensive Management in Grasslands Causes Diffuse Water Pollution at the Farm Scale. Journal of Environmental Quality 43(6): 2009-2023.

Posthumus, H., Deeks, L. K., Fenn, I. & Rickson, R. J. (2011). SOIL conservation in two English catchments: linking soil management with policies. Land Degradation & Development 22(1): 97-110.

Richard, G., Boizard, H., Roger-Estrade, J., Boiffin, J. & Guerif, J. (1999). Field study of soil compaction due to traffic in northern France: pore space and morphological analysis of the compacted zones. Soil & Tillage Research 51(1-2): 151-160.

Riley, H., Pommeresche, R., Eltun, R., Hansen, S. & Korsaeth, A. (2008). Soil structure, organic matter and earthworm activity in a comparison of cropping systems with contrasting tillage, rotations, fertilizer levels and manure use. Agriculture Ecosystems & Environment, 124, 275-284.

Roger-Estrade, J., Richard, G., Caneill, J., Boizard, H., Coquet, Y., Defossez, P. & Manichon, H. (2004). Morphological characterisation of soil structure in tilled fields: from a diagnosis method to the modelling of structural changes over time. Soil & Tillage Research 79(1): 33-49.

Schjønning, P.; Heckrath, G. and Christensen, B.T. (2009). Threats to soil quality in Denmark- A review of existing knowledge in the context of the EU Soil Thematic Strategy. DJF Report Plant Science, no. 143. Aarhus University, Faculty of Agricultural Sciences, Research Centre Foulum, Tjele, Denmark.

Scottish Government. (2009). The Scottish Soil Framework Directive. Scottish Government, Edinburgh, UK, 63 pp.

SEPA. (2015). SEPA position statement on land protection (Reference EP 054). http://www.sepa.org.uk/media/159201/ep-054_position_statement_on_land_protection.pdf. Accessed 18 May, 2015.

SEPA. (2002). The future of Scotland's Waters: Guiding principles on the technical requirements of the Water Framework Directive. A consultation document issued by the Scottish Environment Protection Agency, May 2002. 80 pp.

Six, J., Bossuyt, H., Degryze, S. & Denef, K. (2004). A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. Soil & Tillage Research 79(1): 7-31.

Stavi, I., Lal, R. & Owens, L. B. (2011). Effects of cattle grazing during the dormant season on soil surface hydrology and physical quality in a moist-temperate region. Ecohydrology 4(1): 106-114.

Stevens, C. J., Quinton, J. N., Bailey, A. P., Deasy, C., Silgram, M. & Jackson, D. R. (2009). The effects of minimal tillage, contour cultivation and in-field vegetative barriers on soil erosion and phosphorus loss. Soil & Tillage Research 106(1): 145-151.

Tisdall, J. M. & Oades, J. M. (1982). Organic-matter and water-stable aggregates in soils. Journal of Soil Science 33(2): 141-163.

Tyson, K. C., Garwood, E. A., Armstrong, A. C. & Scholefield, D. (1992). Effects of field drainage on the growth of herbage and the liveweight gain of grazing beef-cattle. Grass and Forage Science 47(3): 290-301.

Ulen, B., Aronsson, H., Bechmann, M., Krogstad, T., Oygarden, L. & Stenberg, M. (2010). Soil tillage methods to control phosphorus loss and potential side-effects: a Scandinavian review. Soil Use and Management 26(2): 94-107.

Valentine, T. A., Hallett, P. D., Binnie, K., Young, M. W., Squire, G. R., Hawes, C. & Bengough, A. G. (2012). Soil strength and macropore volume limit root elongation rates in many UK agricultural soils. Annals Of Botany 110(2): 259-270.

van den Akker, J. J. H. (2004). SOCOMO: a soil compaction model to calculate soil stresses and the subsoil carrying capacity. Soil and Tillage Research 79(1): 113-127.

van Wesemael, B., Paustian, K., Meersmans, J., Goidts, E., Barancikova, G. & Easter, M. (2010). Agricultural management explains historic changes in regional soil carbon stocks. Proceedings of the National Academy of Sciences of the United States of America 107(33): 14926-14930.

Weir, A. H., Rayner, J. H., Catt, J. A., Shipley, D. G. & Hollies, J. D. (1984). Soil factors affecting the yield of winter-wheat - analysis of results from ICI surveys 1979-80. Journal of Agricultural Science 103(DEC): 639-649.

Wheater, H. & Evans, E. (2009). Land use, water management and future flood risk. Land Use Policy 26: S251-S264.

Wiskow, E. & van der Ploeg, R.R. (2003). Calculation of drain spacings for optimal rainstorm flood control. Journal of Hydrology, 272 : 163–174

Withers, P. J. A., Hodgkinson, R. A., Bates, A. & Withers, C. M. (2006). Some effects of tramlines on surface runoff, sediment and phosphorus mobilization on an erosion-prone soil. Soil Use and Management 22(3): 245-255.

Zhang, B., Horn, R. & Hallett, P. (2005). Mechanical resilience of degraded soil amended with organic matter. Soil Science Society of America Journal 69(3): 864-871.

Zhang, Y., Collins, A. L., Murdoch, N., Lee, D. & Naden, P. S. (2014). Cross sector contributions to river pollution in England and Wales: Updating waterbody scale information to support policy delivery for the Water Framework Directive. Environmental Science & Policy 42: 16-32.

Appendix 2 – Catchment Selection

Background:

With a stakeholder group consisting of government agencies, industry and farmer groups, we identified a long-list of catchments based on previous research, ongoing monitoring and priorities of the agencies. Subsequent GIS analysis based on the soil properties and drainage has allowed a more detailed assessment of these catchments for a robust selection of catchments that: (i) are representative of Scotland's agricultural landscape and (ii) provide extreme instances where soil structural degradation or drainage issues are predicted to be either very problematic or unlikely. This document provides an overview of the selection process.

Long-list of Catchments:

Based on discussions held between the project team and the Stakeholder Group on 15 December at the SEPA Office in Perth, we identified the following long-list, with a brief summary provided about its selection based on expert opinion.

1. **Coyle and East Pow** – both priority catchments and part of a Scottish Government funded project led by SRUC on nutrient management and RAMS (Risk Assessment for Manure and Slurry Spreading) for soils. Both priority catchments – one arable one livestock and good monitoring.

2. **Eddleston** water (River Tweed catchment) - monitoring work on natural flood management but not a first cycle priority catchment

3. **Loch Leven** – SNH farm advisory work round Loch Leven is consistently dealing with issues of soil erosion. Not a first cycle priority catchment due to recovery. Work planned in 2015 on source apportionment. Good monitoring data available.

4. **River South Esk** - impacts of sediment on freshwater pearl mussels are a key concern for SNH in this catchment. Priority catchment and good monitoring available.

5. **Carse of Stirling** – good farmer group here, not a catchment (part of Forth) or a first cycle priority catchment but planned CREW work here on assessing flood risk and working with community, mixed land use including semi-natural.

6. SEPA DPMCs **Lunan and Cessnock** – good monitoring and catchments selected due to representative land use. Lunan not a priority catchment.

7. SEPA pilot catchments – e.g. South Esk, Nith, Dee, Glazert may also be relevant

8. **Ugie** – mixed arable and livestock, priority for Scottish Water – a Sustainable Land Management catchment, part of CREW assessment of catchment management measures to reduce the costs of drinking water project. Good monitoring data available.

Using SEPA catchment boundaries and soil data, a more detailed analysis allowed selection of the 4 catchments to investigate.

Initial Screening – Size, Land Use and Location

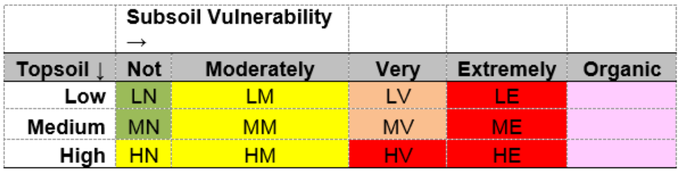
To allow feasible field sampling, a cut-off of 600 km^2 was taken, with at least 25% of the land under agricultural production. Arable farming percentages varied considerably, with particularly small proportions in SW Scotland. We incorporated Coyle over Cessnock due to its size, proportion of arable land and previous work identifying challenging soil physical conditions (Table A2:1).

Soil Compaction Vulnerability

We are interested in a range of compaction vulnerabilities when selecting farms for sampling. A predictive model developed by Jones et al. (2003) of subsoil compaction vulnerability and a model to predict the risk of topsoil compaction (Ball, 1985 & 1986) were applied using data on soil physical behaviour due to its inherent textural and structural properties, as well as annual climatic conditions. To our knowledge, this modelling exercise is the first time the subsoil compaction vulnerability assessment has been applied at this scale in Scotland, as previous research focussed on much larger land areas. A broad range of soil compaction vulnerability classes are derived with this approach, which we simplified using a 'traffic light' system defined below. It incorporated both Topsoil and Subsoil, with all Extremely Vulnerable Subsoil Compaction being assigned red due to the greater challenge in ameliorating damage beneath the plough layer (Figure A2:1). It should be noted that no areas of any catchments were identified as not being vulnerable to soil compaction.

		Percentage Land Area			
Catchment	**Catchment Area (km^2)**	**Agriculture**	**Arable**	**Improved Grassland**	**Geographic Location**
Cessnock	76	73	7	66	SW - Ayrshire
Coyle	81	48	10	37	SW - Ayrshire
East Pow	48	66	43	22	C - Perthshire
Eddleston	69	36	8	28	SE- Borders
Glazert	53	18	2	16	C - Dunbartonshire
Loch Leven	159	60	26	34	C - Perthshire
Lunan	134	80	66	14	E - Angus
South Esk	563	29	21	8	E - Angus
Ugie	335	67	34	32	NE - Aberdeenshire
Carse of Stirling	318	31	16	15	C - Stirling
Nith	1115	18	6	13	SW - Dumfries
Tarland	74	39	15	25	NE - Deeside

Table A2:1 - Long-list of catchment sizes and the proportion of land under different land uses. The locations cover major agricultural areas of Scotland. Red text indicates that the catchment has been excluded as certain criteria were not met.



	Subsoil Vulnerability →				
Topsoil ↓	Not	Moderately	Very	Extremely	Organic
Low	LN	LM	LV	LE	
Medium	MN	MM	MV	ME	
High	HN	HM	HV	HE	

Figure A2:1 – Traffic light system from green to red to summarise the vulnerability of soil to compaction

The soil compaction predictive model identified the Coyle as the most vulnerable catchment within the long list identified by the stakeholders (Table A2:2). This corresponds with expert opinion concerning soil physical degradation in this catchment and the challenges faced by farmers. Any catchments with a combined Amber and Red compaction vulnerability <25% were also identified and eliminated from selection since they would provide an insufficient area of vulnerable soils.

HOST Drainage Classes

Hydrology of Soil Types, HOST, classifies the soils of the United Kingdom into 29 categories (Boorman et al., 1995). These classes are based on a series of conceptual models that simulate the hydrological behaviours due to inherent soil physical properties (e.g. hydraulic conductivity), position in the landscape and climate. They are valuable for estimating base flow index and standard percentage runoff (SPR). Soils with a high SPR likely produce greater erosion, with impacts of surface damage having a larger impact on flood risk. The classifications identified during our analysis of the catchments are shown in Table A2:3.

The HOST mapping indicated that poor drainage and surface run-off would affect most of the catchments identified in the long-list. Tarland is the only catchment that can be excluded based on HOST drainage classes, as it has at least 88% of its area with an SPR <25.

Catchment	Green	Yellow	Amber	Red	Other
Cessnock	0	94	1	2	3
Coyle	0	57	2	37	3
East Pow	0	69	22	8	0
Eddleston	0	10	69	18	3
Glazert	0	65	9	17	9
Loch Leven	0	55	25	18	1
Lunan	0	61	29	9	0
South Esk	0	48	37	14	1
Ugie	0	68	14	11	7
Carse of Stirling	0	78	**7**	**7**	8
Nith	0	10	52	17	22
Tarland	0	47	13	34	6

Table A2:2 – Long-list of catchments summarising the vulnerability to soil compaction based on the traffic light system described in Figure 1. Bold indicates selection due to high vulnerability.

HOST Class	Conceptual Model	SPR, %
4	No Impermeable or gleyed layer within 1 m. Ground water/Aquifer normally >2 m deep. Some surface Runoff / Vertical unsaturated flow.	19.4
5		12.2
6		29.1
13	Impermeable layer within 1m or gleyed at 40 - 100cm. Ground water normally >2 m deep. Some surface runoff / Seasonal saturated flow/ Mainly vertical unsaturated flow.	5.5
14	Gleyed within 40 cm. Ground water normally >2 m deep. Surface runoff likely / Prolonged seasonal saturated flow / Leakage to substrate.	46.7
16	No Impermeable or gleyed layer within 1 m. No significant Ground water or Aquifer. Surface runoff likely / Vertical unsaturated and bypass flow.	20.3
17		31.5
18	Impermeable layer within 1m or gleyed at 40 - 100cm No significant Ground water or Aquifer. Surface runoff likely / Seasonal saturated flow / Some seasonal unsaturated and bypass flow to substrate.	37.6
24	Gleyed within 40 cm. No significant Ground water or Aquifer. Surface runoff likely / Prolonged seasonal saturated flow / Short seasonal unsaturated and bypass flow to substrate.	51.3

Table A2:3 – HOST classes indicating drainage conditions of the catchments and the standard percentage run off (SPR).

	HOST Class								
Catchment	4	5	6	13	14	16	17	18	24
Cessnock									96
Coyle									94
East Pow	18							57	
Eddleston		17					52		27
Glazert		12			12				39
Loch Leven		23					24	26	
Lunan		13	25					54	
South Esk		10	22			10		47	
Ugie				10			39		31
Carse of Stirling						16			50
Nith		16					22		10
Tarland		10		10		68			

Table A2:4 – Percentage of catchment areas designated specific HOST classes. Red indicates elimination of the catchment due to a large percentage of land area with SPR <25

Soil Distribution

Catchment selection needs to be representative of soils under agricultural production in Scotland. Brown earths are the most prominent, but agriculture occurs on all soil types listed in Table A2:5.

Catchment	Alluvial soils	Brown earths	Gleys	Podzols
Cessnock			96	
Coyle		29	71	
East Pow		80		15
Eddleston		69	28	
Glazert	19	30	51	
Loch Leven		58		29
Lunan		42		53
South Esk		30		66
Ugie		**23**	**36**	**37**
Carse of Stirling		43	51	
Nith	14	71	14	
Tarland		55	7	39

Table A2:5 – Percentage of land area in catchments covered with different soil types representative of major agricultural soils in Scotland

We have selected the Ugie due to the distribution of 3 soil types within one catchment. There is no limitation due to soil types that affects selection of any of the remaining catchments that have not yet been excluded.

Catchment Selection

Based on the criteria used thus far, 7 catchments remain that can be selected (Table A2:6). The Coyle was selected due to compaction vulnerability and evidence of soil physical damage in practice. The Ugie provides a broad range of soil types. These two catchments represent SW and NE Scotland, so to ensure geographic spread we have identified two catchments from other regions. East Pow is a contained catchment in central Scotland, chosen over Loch Leven for ease of sampling. South Esk covers the largest area of the remaining catchments. It was identified by the stakeholder group as a preferred area to sample due to ongoing monitoring work in place by SEPA.

Farm Selection

Detailed maps of soil types, topography, HOST and compaction that were produced allowed for a range of farms to be identified with different vulnerabilities to water quality (run-off), drainage and soil compaction. Each catchment was also being visited for a visual assessment of selected farms before the survey got underway. Monitoring also occurred in summer 2015 at South Esk Farms by University of Aberdeen MSc students. This was additional to the agreed deliverables of the project.

Catchment	Catchment Area (km^2)	Geographic Location
Cessnock	76	SW - Ayrshire
Coyle	**81**	**SW - Ayrshire**
East Pow	**48**	**C - Perthshire**
Eddleston	69	SE- Borders
Glazert	53	C - Dunbartonshire
Loch Leven	159	C - Perthshire
Lunan	134	E - Angus
South Esk	**563**	**E - Angus**
Ugie	**335**	**NE - Aberdeenshire**
Carse of Stirling	318	C - Stirling
Nith	115	SW - Dumfries
Tarland	74	NE - Deeside

Table A2:6 – Catchment short-list showing the 4 preferred locations.

References

Ball, B.C. (Compiler) (1985). Cultivation requirements for Winter barley. SAC/MISR/SIAE publication 154. Scottish Agricultural Colleges. Edinburgh.

Ball, B.C. 1986. Provisional land grouping for selection of cultivation requirements for Winter barley in Scotland. Soil and Tillage Research, 7: 7-18.

Boorman, D.B., Hollis. J.M. & Lilly, A. (1995). Hydrology of soil types: a hydrologically based classification of the soils of the United Kingdom. Institute of Hydrology Report No. 126.

Jones, R. J. A., Spoor, G. & Thomasson, A. J. (2003). Vulnerability of subsoils in Europe to compaction: a preliminary analysis. Soil and Tillage Research, 73: 131-143.

Stakeholder Group:

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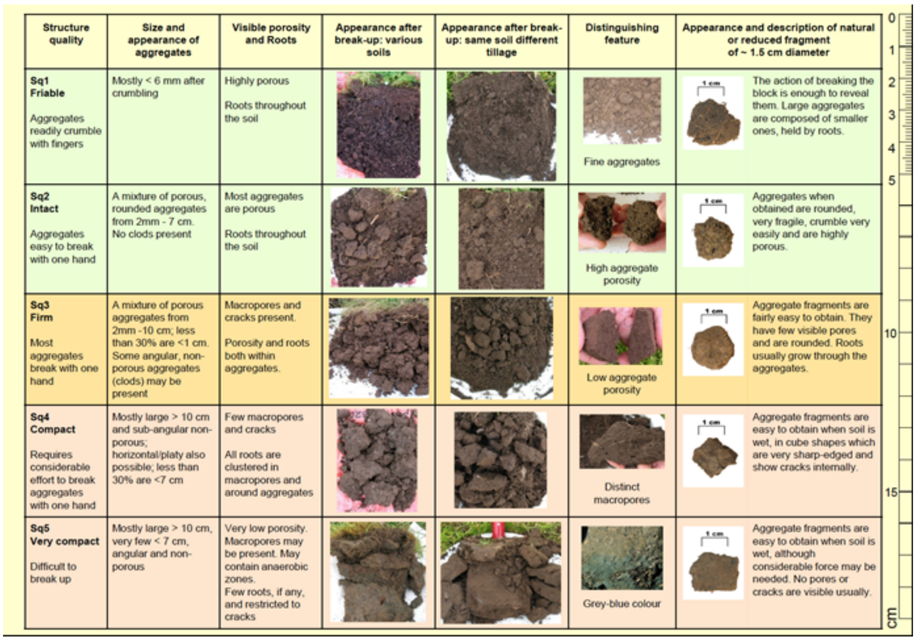
Heather Forbes, SEPA
Gavin Dick, HGCA
Patricia Bruneau, SNH
Alan Cundill, SEPA
Zoe Frogbrook, Scottish Water
Andrew Bauer, NFUS

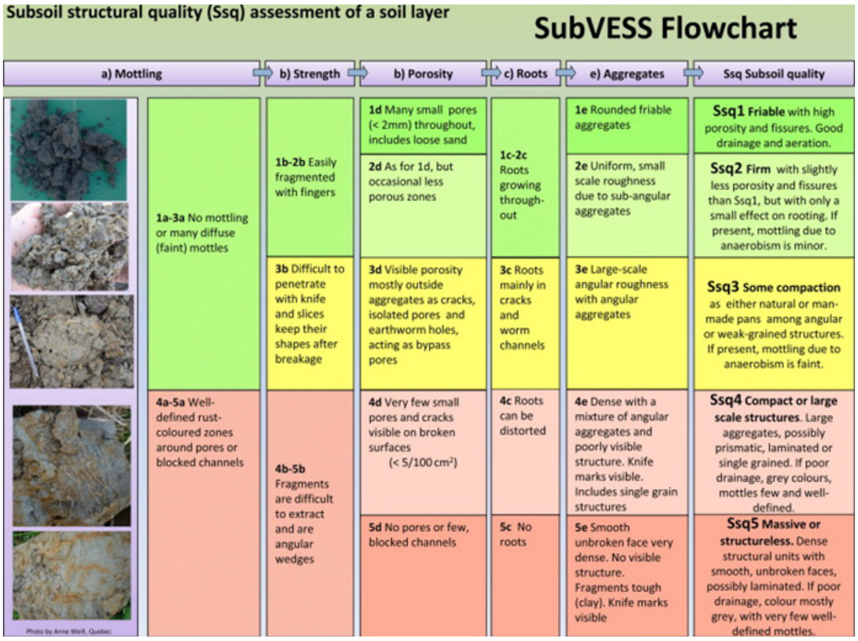
Appendix 3 – Visual Soil Structure Assessment

a. The VESS Scoring Sheet



Structure quality	Size and appearance of aggregates	Visible porosity and Roots	Appearance after break-up: various soils	Appearance after break-up: same soil different tillage	Distinguishing feature	Appearance and description of natural or reduced fragment of ~ 1.5 cm diameter
Sq1 Friable Aggregates readily crumble with fingers	Mostly < 6 mm after crumbling	Highly porous Roots throughout the soil			Fine aggregates	The action of breaking the block is enough to reveal them. Large aggregates are composed of smaller ones, held by roots.
Sq2 Intact Aggregates easy to break with one hand	A mixture of porous, rounded aggregates from 2mm - 7 cm. No clods present	Most aggregates are porous Roots throughout the soil			High aggregate porosity	Aggregates when obtained are rounded, very fragile, crumble very easily and are highly porous.
Sq3 Firm Most aggregates break with one hand	A mixture of porous aggregates from 2mm -10 cm; less than 30% are <1 cm. Some angular, non-porous aggregates (clods) may be present	Macropores and cracks present. Porosity and roots both within aggregates.			Low aggregate porosity	Aggregate fragments are fairly easy to obtain. They have few visible pores and are rounded. Roots usually grow through the aggregates.
Sq4 Compact Requires considerable effort to break aggregates with one hand	Mostly large > 10 cm and sub-angular non-porous; horizontal/platy also possible; less than 30% are <7 cm	Few macropores and cracks All roots are clustered in macropores and around aggregates			Distinct macropores	Aggregate fragments are easy to obtain when soil is wet, in cube shapes which are very sharp-edged and show cracks internally.
Sq5 Very compact Difficult to break up	Mostly large > 10 cm, very few < 7 cm, angular and non-porous	Very low porosity. Macropores may be present. May contain anaerobic zones. Few roots, if any, and restricted to cracks			Grey-blue colour	Aggregate fragments are easy to obtain when soil is wet, although considerable force may be needed. No pores or cracks are visible usually.

b. The SubVess Flowchart



Subsoil structural quality (Ssq) assessment of a soil layer

SubVESS Flowchart

a) Mottling		b) Strength	b) Porosity	c) Roots	e) Aggregates	Ssq Subsoil quality
	1a-3a No mottling or many diffuse (faint) mottles	**1b-2b** Easily fragmented with fingers	**1d** Many small pores (< 2mm) throughout, includes loose sand	**1c-2c** Roots growing through-out	**1e** Rounded friable aggregates	**Ssq1 Friable** with high porosity and fissures. Good drainage and aeration.
			2d As for 1d, but occasional less porous zones		**2e** Uniform, small scale roughness due to sub-angular aggregates	**Ssq2 Firm** with slightly less porosity and fissures than Ssq1, but with only a small effect on rooting. If present, mottling due to anaerobism is minor.
		3b Difficult to penetrate with knife and slices keep their shapes after breakage	**3d** Visible porosity mostly outside aggregates as cracks, isolated pores and earthworm holes, acting as bypass pores	**3c** Roots mainly in cracks and worm channels	**3e** Large-scale angular roughness with angular aggregates	**Ssq3 Some compaction** as either natural or man-made pans among angular or weak-grained structures. If present, mottling due to anaerobism is faint.
	4a-5a Well-defined rust-coloured zones around pores or blocked channels	**4b-5b** Fragments are difficult to extract and are angular wedges	**4d** Very few small pores and cracks visible on broken surfaces (< 5/100 cm²)	**4c** Roots can be distorted	**4e** Dense with a mixture of angular aggregates and poorly visible structure. Knife marks visible. Includes single grain structures	**Ssq4 Compact or large scale structures.** Large aggregates, possibly prismatic, laminated or single grained. If poor drainage, grey colours, mottles few and well-defined.
			5d No pores or few, blocked channels	**5c** No roots	**5e** Smooth unbroken face very dense. No visible structure. Fragments tough (clay). Knife marks visible	**Ssq5 Massive or structureless.** Dense structural units with smooth, unbroken faces, possibly laminated. If poor drainage, colour mostly grey, with very few well-defined mottles.

Photo by Anne Weil, Quebec

Appendix 4 – ‘In Field’ monitoring form

FARM ID:

Locality:

Date: | **Site:** | **Grid Ref:**

Elevation: | **Land Use:** | **Crop Cover:**

Slope: | **Soil Series**

Erosion: Severe: ☐ Moderate: ☐ Visible: ☐☐☐☐☐☐ Not Visible: ☐

Visual Soil Structure

Depth:

Soil Surface:

Eroded: ☐ Slaked: ☐ Poached: ☐
Stable:☐

Topsoil Shallow:

Topsoil Deep:

Interface:

Subsoil:

Topsoil Depth: | **Texture:** | Plasticity:

Subsoil Texture: | **Subsoil Plasticity:**

Surface Drainage: Standing Water: ☐ Water-logged: ☐ Wet: ☐
Drained: ☐

Subsurface Drainage: Standing Water: ☐ Water-logged: ☐ Wet: ☐
Drained: ☐

Tillage/Livestock Status:

Grass: ☐ Harvested Root: ☐ Stubble: ☐ Ploughed Bare: ☐
Winter Cereal: ☐

Additional Comments:

Appendix 5 – Additional Figures for Field Soil Structure Assessments

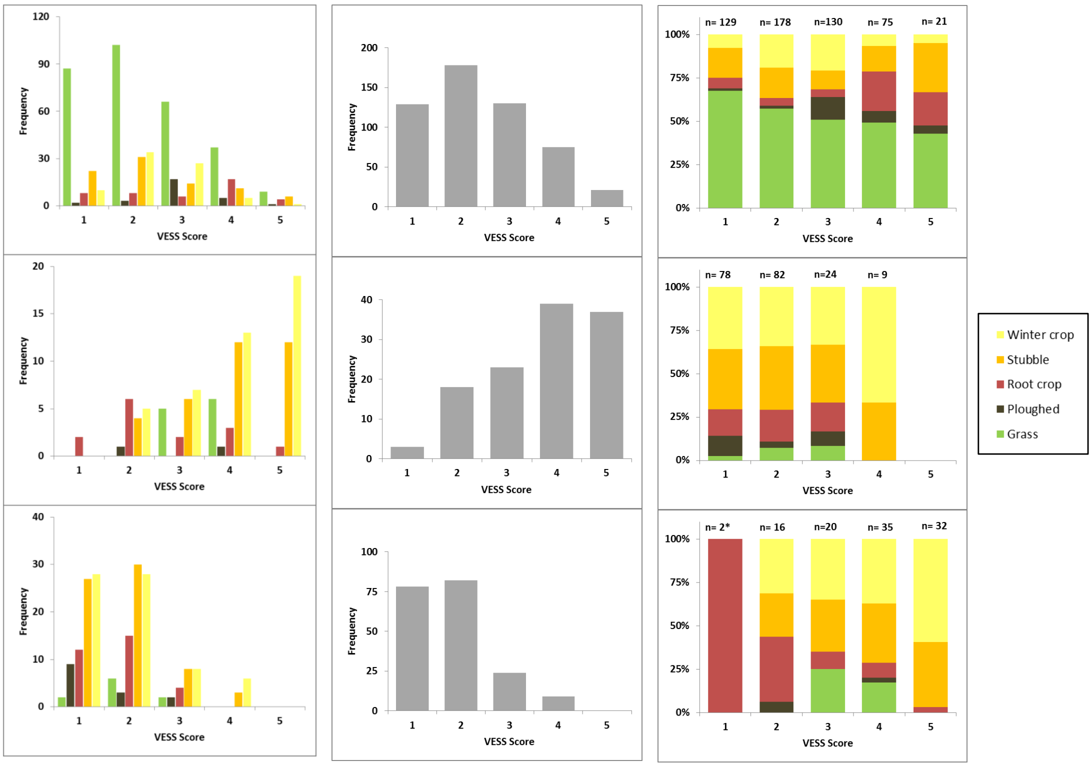


Figure A5:1: Frequency distribution of the VESS scores separated by cropping practice for '*In Field*' (Top), '*Damaged*' (Middle) and '*Margins*' (Bottom). VESS ≤ 2 indicates good topsoil structural condition, whereas ≥ 4 indicates severe degradation.

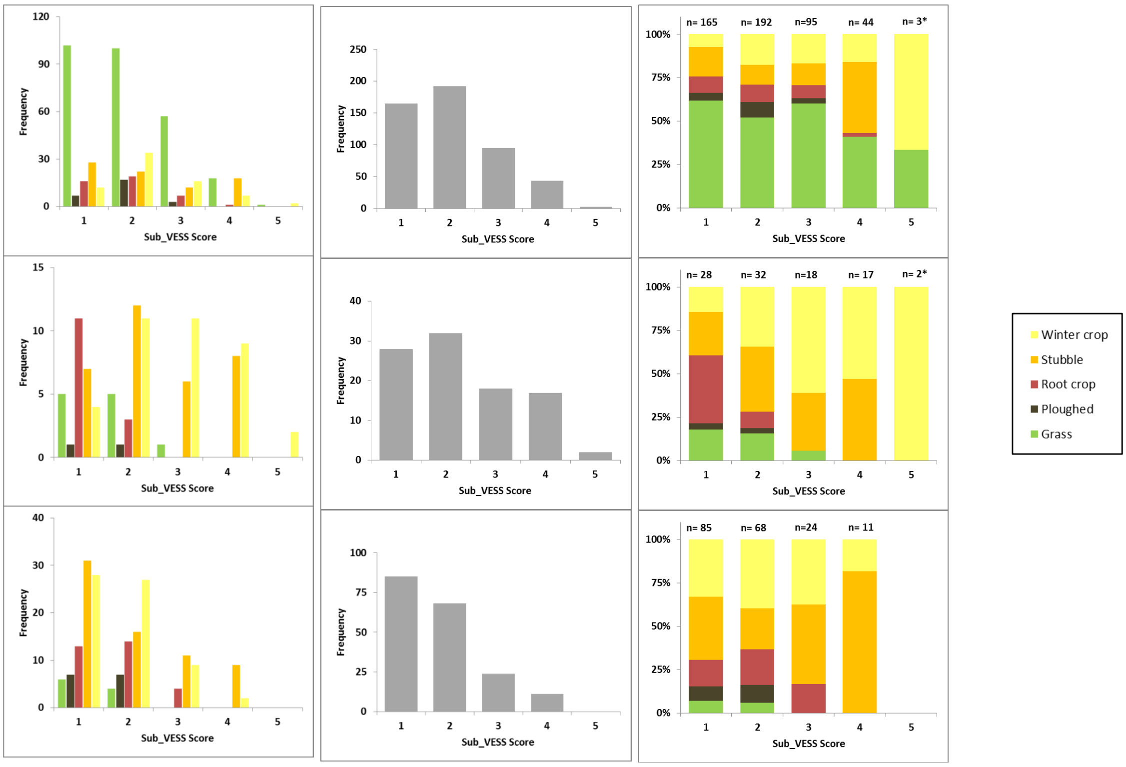


Figure A5:2 - Frequency distribution of the SubVESS scores separated by cropping practice after the extreme December/January precipitation for '*In Field*' (Top), '*Damaged*' (Middle) and '*Margins*' (Bottom). SubVESS ≤ 2 indicates good subsoil structural condition, whereas ≥ 4 indicates severe degradation.

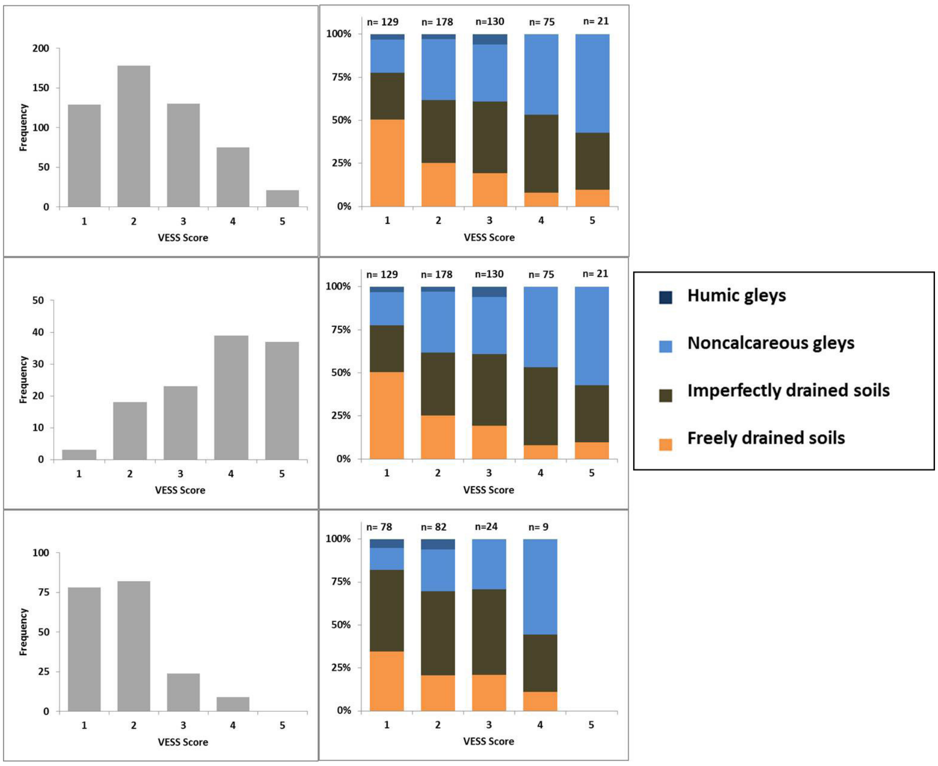


Figure A5:3 - Frequency distribution of the VESS scores separated by major soil types for '*In Field*' (Top), '*Damaged*' (Middle) and '*Margins*' (Bottom). VESS ≤ 2 indicates good topsoil structural condition, whereas ≥ 4 indicates severe degradation. Imperfectly and freely drained soils includes Podzols and Brown earths.

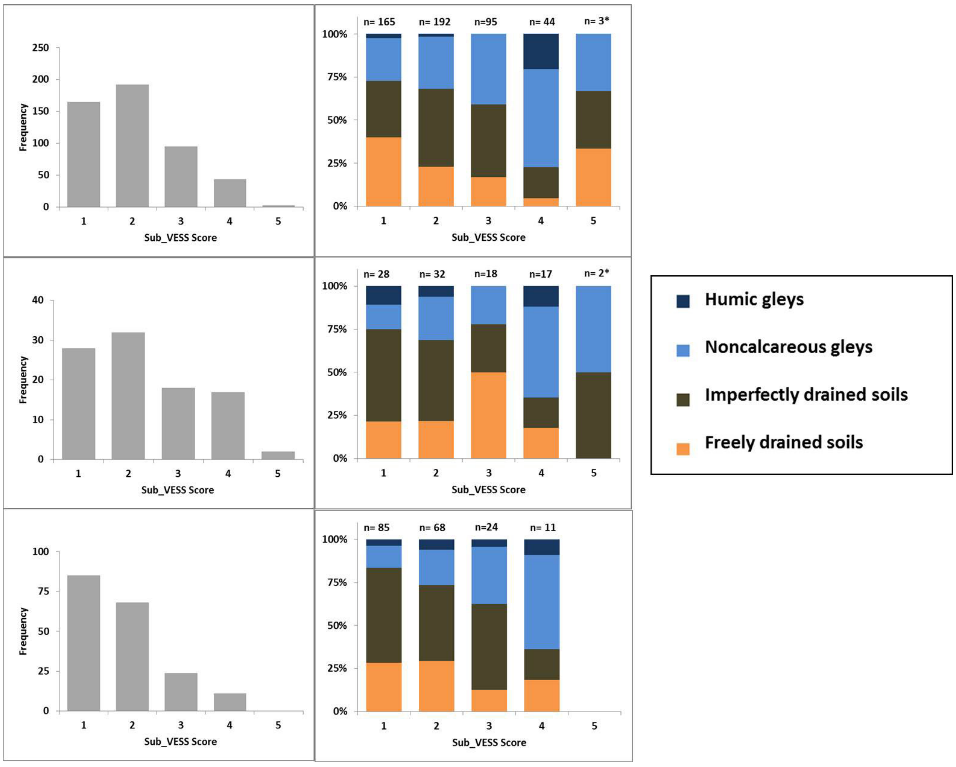
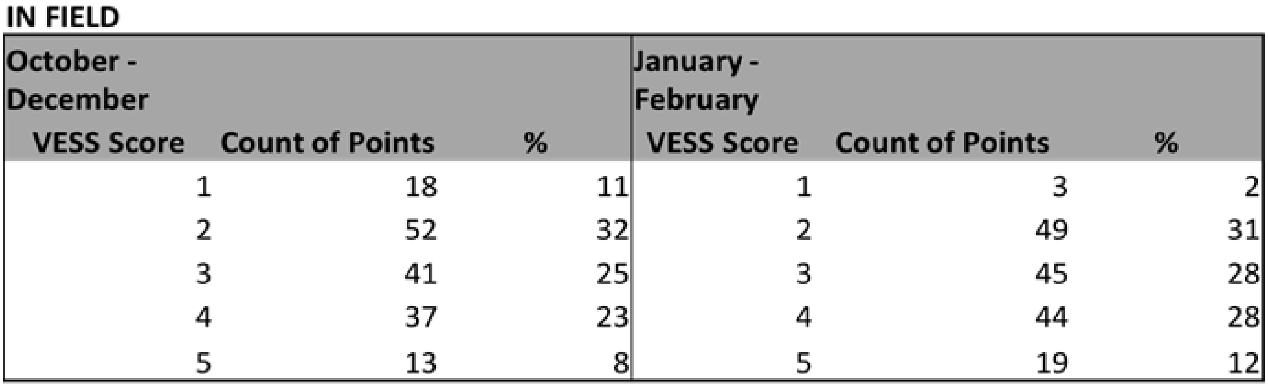
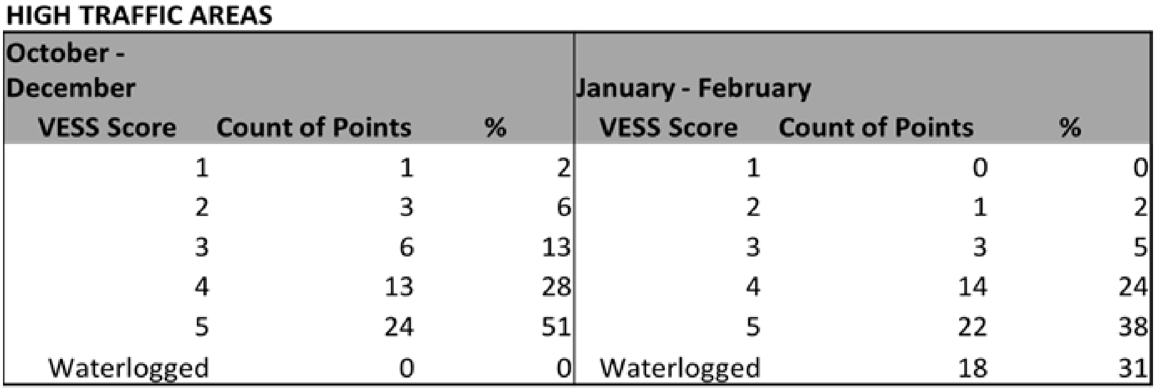


Figure A5:4 - Frequency distribution of the SubVESS scores separated by major soil types after the extreme December/January precipitation for '*In Field*' (Top), '*Damaged*' (Middle) and '*Margins*' (Bottom). SubVESS ≤ 2 indicates good subsoil structural condition, whereas ≥ 4 indicates severe degradation. Imperfectly and freely drained soils includes Podzols and Brown earths.



IN FIELD

October - December VESS Score	Count of Points	%	January - February VESS Score	Count of Points	%
1	18	11	1	3	2
2	52	32	2	49	31
3	41	25	3	45	28
4	37	23	4	44	28
5	13	8	5	19	12



HIGH TRAFFIC AREAS

October - December VESS Score	Count of Points	%	January - February VESS Score	Count of Points	%
1	1	2	1	0	0
2	3	6	2	1	2
3	6	13	3	3	5
4	13	28	4	14	24
5	24	51	5	22	38
Waterlogged	0	0	Waterlogged	18	31

Table A5:1 - Raw data showing the change in topsoil VESS before and after the extreme precipitation event in Scotland in January 2016.

Appendix 6 – Field Drainage Assessment

FARM ID:

Locality: **Surveyor:**

Date: **Site:** **Grid Ref:**

Farm Manager Questions

Extent of installed artificial drainage –

Tiled drain diversion ☐ (or) Piped drainage scheme ☐
- Plastic ☐
- Clay ☐

Is there gravel/stone? Yes ☐ No ☐

Are outfalls clear? Yes ☐ No ☐ (*When where ditches last cleared?*)

Functioning: Excellent ☐ Moderate ☐ Poor ☐

Surveyor Assessment

Weather: Clear for 2 days ☐ Rained w/in 2 days ☐ Raining ☐ Snow ☐

Drain outlets:
Clear/Free Flowing ☐ Slow Flow/Sediment ☐ Blocked ☐ Not found ☐

General Observations:

History of drainage systems –

Appendix 7 – Farmer Questionnaire on Drainage

FARM ID:

Locality: **Surveyor:**

Date: **Site:** **Grid Ref:**

Drainage System:

What drainage system do you use?

Open field ditches ☐ In field sub surface drainage pipes ☐
Mole drains ☐

Other:

When was it installed?

When was it last replaced?

Do you have records? Yes ☐ No ☐

Is current land drainage the major restriction on yield? Yes ☐ No ☐

Does your field need more drainage? Yes ☐
No ☐

What areas of the farm are drained?

Management and maintenance:

Who operates and maintains the drainage system?

How often is your drainage system maintained?
0-1 years ☐ 2-5 years ☐ 5-10 years ☐ 10 years + ☐
Never ☐

What drain maintenance do you use?
Jet washing ☐ Sub soiling ☐ Unblocking ☐ Other:

Approximately, how much have you spent on drain maintenance or upgrade in this field?

____

Is ochre a problem? Yes ☐ No ☐

Upgrade and replacement:

Are you willing to change or update your drainage systems? Yes☐
No ☐

Do you view the current drainage system as degraded? Yes ☐
No ☐

Do you view drainage as a major expense? Yes ☐
No ☐

Appendix 8 – Farm Report Template

Title

Prepared for:
Prepared by:
Date:

Introduction

This report is formed as part of Scotland's Centre of Expertise for Water (CREW) "Effect of Soil Structure and Field Drainage on Water Quality and Flood Risk" project. The findings of this report are based on visual soil and drainage assessments of three fields on (insert Farm name) farm on (dd/mm/2015). Methods used in this report are; Visual Evaluation of Soil Structure (VESS and SubVESS, shown in appendix 1), visual assessments of current drainage systems, and questionnaires completed by (Farmer – if applicable), Rebecca Hall and (Surveyor 2). This report does not provide guidance or recommendations to future soil and drainage management.

Drainage

Overview of drainage and visual evaluation (2 paragraphs) – attach copied drainage questionnaire.

(Field 1 findings)

Soil description: (Texture: /Type: /Series :)
Plough depth:
Compaction Risk from soil maps and models: topsoil, (enter); subsoil, (enter).
Note: due to the resolution of data used that this may not reflect your local farm conditions.
Overall field margin SQ score: Top soil; (enter), Sub soil; (enter), (See appendix 1 for VESS score guide).
Overall infield SQ score: topsoil, (enter); sub soil, (enter).
Overall degraded area SQ score: topsoil, (enter); sub soil, (enter).

(Field 2 findings)

Soil description: (Texture: /Type: /Series :)
Plough depth:
Compaction Risk; topsoil, (enter); sub soil, (enter).
Overall field margin SQ score: topsoil, (enter); sub soil, (enter).
Overall infield SQ score: topsoil, (enter); sub soil, (enter).
Overall degraded area SQ score: topsoil, (enter); sub soil, (enter).

(Field 3 findings)

Soil description: (Texture: /Type: /Series :)
Plough depth:
Compaction Risk; topsoil, (enter); sub soil, (enter).
Overall field margin SQ score: topsoil, (enter); sub soil, (enter).
Overall infield SQ score: topsoil, (enter); sub soil, (enter).
Overall degraded area SQ score: topsoil, (enter); sub soil, (enter).

Summary

Appendix 9 - Testing the use of Landsat 8 data for surface drainage in agricultural soils in Scotland

As part of the work to identify drainage condition on agricultural soils in four catchments across Scotland, there was interest in finding out if remote sensing could provide useful data for detection of poor soil drainage due to compromised drainage systems. As the ultimate goal of this, if successful, would be to provide mapping across Scotland for agricultural soils the remote sensing data would need to be freely available, relatively high resolution and with sufficient spectral wavelength bands to allow soil moisture condition and vegetation cover to be assessed. It would also need to be relatively recent data and provide repeat data over short timescales (within a growing season). Landsat 8 (launched late 2014, operational since May 2015) satisfies these requirements.

Methods

Landsat data

Two Landsat 8 scenes were acquired that were captured in late 2015, and which covered the full areas of the four catchments. The imagery is of 30 metre resolution and contains wavelength bands in the visible, near-infrared and mid-infrared. A number of candidate scenes were downloaded that covered the areas of interest, and the best ones selected in terms of haze and cloud cover.

Field data

Several hundred data points were available from the field work carried out, with a total of 831 being available. Of these, 567 lay inside the catchment boundaries where mapping was carried out (see below) and 545 were both inside the catchment boundaries and had RS data available (there was a small number of 'dropped' pixels from the Landsat data). For the field data, Surface Drainage only was selected to provide information that would relate to what was visible with remote sensing. Subsurface parameters and other characteristics were not considered viable for this kind of work.

NDVI

The NDVI was calculated for each pixel in the two scenes. This parameter is related closely to above-ground biomass (due to the absorption of red light and reflectance of near-infrared by vegetation), and is a good indicator of bare ground. It is calculated as a ratio of visible (red) wavelengths to near-infrared, and is calculated as (NIR-VIS)/(NIR+VIS). This gives a dimensionless value in the range [-1, 1], with lower values (those below 0 are rarely seen) having lower biomass. The purpose of using NDVI was to allow us to identify those sites where the soil was visible and therefore unobstructed by vegetation for estimation of moisture content.

Temperature calculation

Surface temperature calculation was calculated using an adjusted version of the method given in http://www.yale.edu/ceo/Documentation/Landsat_DN_to_Kelvin.pdf. As the Landsat 8 data is given in 16-bit (0-65535) rather than 8-bit (0-255), the relationship between reflectance digital number D in the thermal band (Band 10) and surface temperature T is given by:

$T = 1260 / \log_e((617.5 / ((0.05518 \times D / 255) + 1.2378)) + 1)$ (**equation 1**)

This temperature estimate is considered a proxy of soil moisture content, as soils with higher moisture content will have higher specific heat capacity and will therefore be colder than those soils with low moisture content. Landsat imagery is captured at approximately 10.30 am every morning as the satellite passes over, and so soils will be warming up at that time from night-time cooling. This approach does not give a direct measurement of soil temperature or moisture content, but does allow local variation to be detected.

Estimating surface drainage

For soils with low NDVI values (below 0.1) that are not obscured by vegetation cover, it was assumed that poor drainage would be indicated by wetter conditions and lower temperatures. Estimated temperatures were adjusted for elevation, by adding 1°C for every 100 metres in elevation above sea level.

Results

Erosion

Figure A9:1 shows the relationship between NDVI and erosion category, with higher values in this category indicating worse erosion. As can be seen, worse erosion has low NDVI values as expected. However, sites with little or no erosion were found to cover the full range of NDVI values, and so it is not possible to categorically state that low NDVI indicates worse erosion.

Surface drainage

Figure A9:2 shows the relationship between estimated temperature (expressed as the difference between pixel temperature and the elevation-adjusted scene minimum) and soil drainage category, with higher values of drainage category indicating poorer drainage. This shows a definite relationship between temperature (and therefore moisture content) and drainage category, with poorer drainage being colder and therefore wetter. There is a lot of variation visible within the temperatures seen at each drainage category, and it is assumed that a number of other factors are important (such as soil texture and slope/aspect).

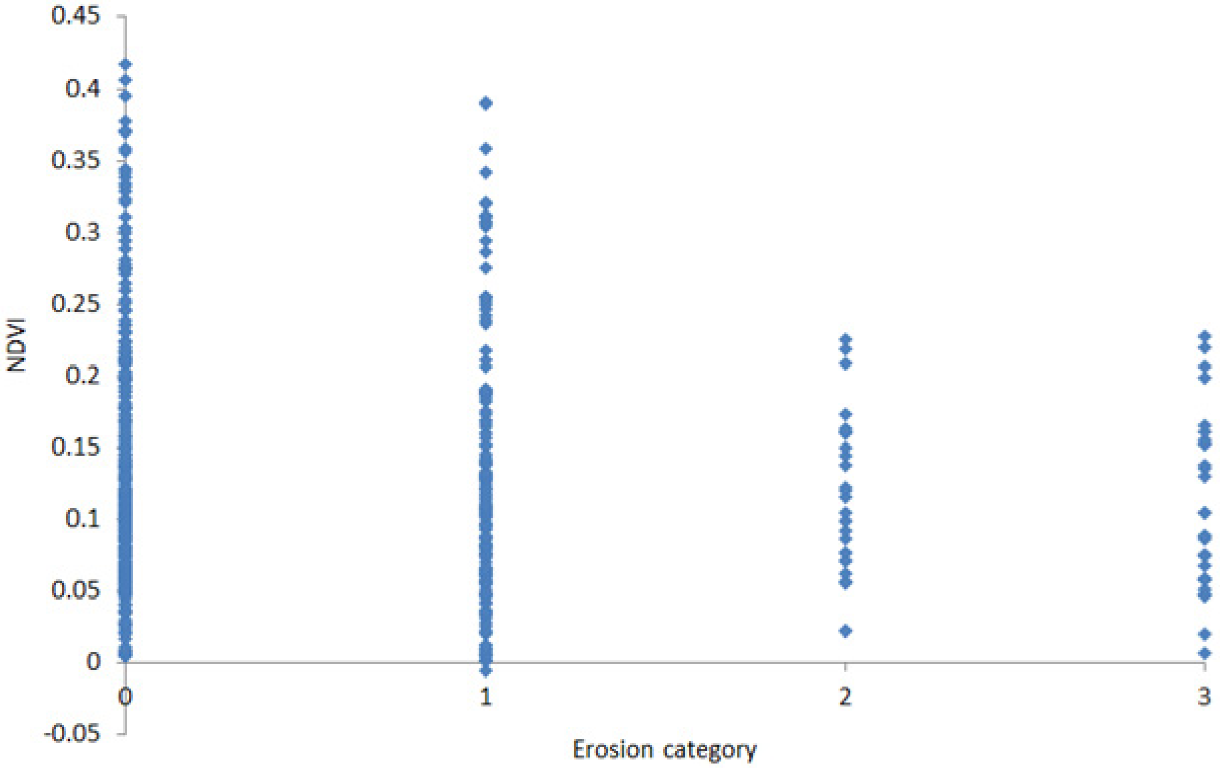


Figure A9:1 - Erosion category to NDVI, with higher values indicating greater erosion.

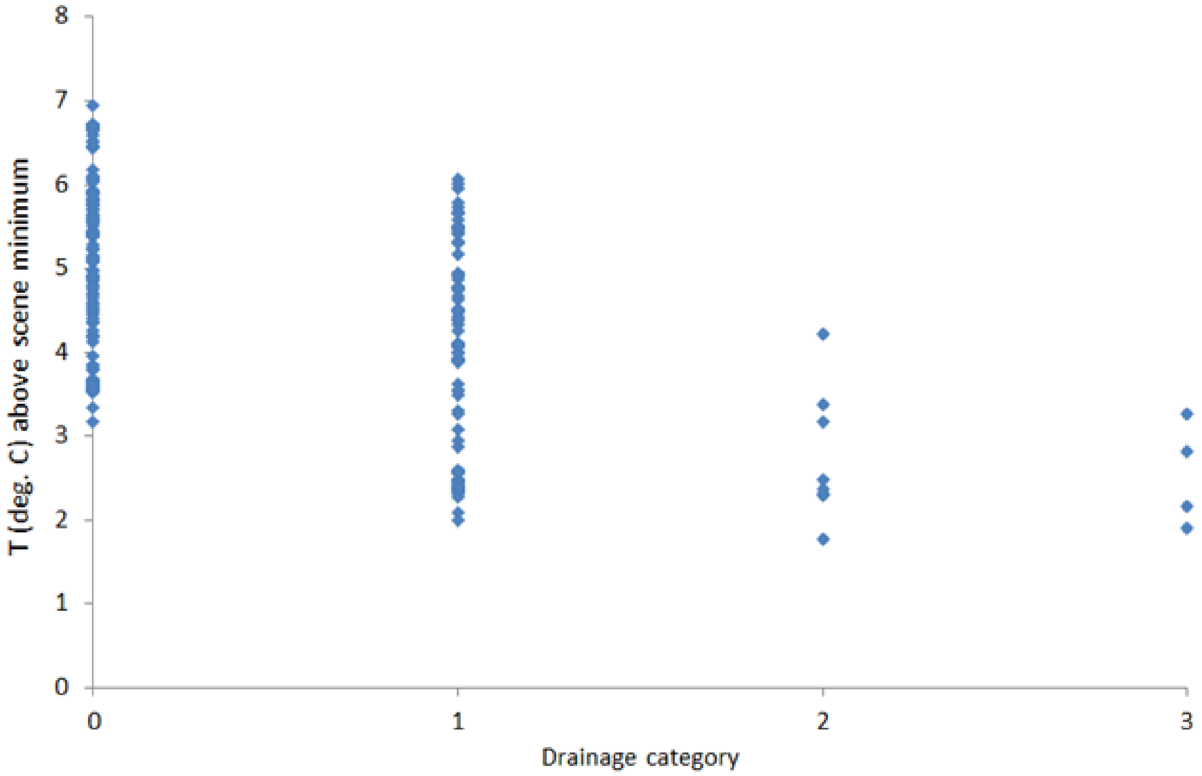


Figure A9:2 - Relationship between drainage category and temperature above local minimum, with higher

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